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CORRIGENDA

Vol. 69, page 1221, col. 2, line 21: *For* "Table 3" *read* "Table B."

,, 70, pages 365, 379, and 381: *For* "Weischel" *read* "Weichsel."

,, 70, page 473, col. 2, line 22: *For* "25th January" *read* "21st January."

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THE JOURNAL OF
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VOL. 71.

THE ABSOLUTE MEASUREMENT OF HIGH ELECTRICAL PRESSURES.

By Prof. W. M. THORNTON, O.B.E., D.Sc., D.Eng., Member, and W. G. THOMPSON, Ph.D., B.Sc., Graduate.

(*Paper first received* 30*th April, and in final form* 28*th July*, 1931; *read before* THE INSTITUTION 21*st January, and before the* NORTH-EASTERN CENTRE 11*th January*, 1932.)

SUMMARY.

There is at present no absolute standard method of measurement by which the high voltages now in common use may be compared. The paper gives an account of such a method in which the polarization of a metallic ellipsoid of revolution, suspended by an insulating fibre between vertical circular pole-plates, is observed. The dimensions and proportions of the ellipsoid and of the horizontal field were determined with high accuracy, and the magnitude of the electric gradient on the axis of symmetry of the instrument was calculated for given applied voltages. The working formula of the instrument is $F = k(n^2 - n_0^2)^{\frac{1}{2}}$, where F is the field strength, k a constant found from the dimensions, n the number of swings per second of the ellipsoid with the field on and n_0 with it off. The influence of the spacing of the plates, of shielding the ellipsoid, of gas pressure and temperature, was examined, and the readings of the instrument were compared with Whitehead and Castellain's sphere-gap determinations of voltage. As a combined check on the accuracy of their readings and those of this instrument, a value of the ratio c of the electromagnetic to the electrostatic units of quantity is obtained which agrees with the best previous results. It is concluded that continuous measurements of voltages up to 200 kV can be made with the precautions indicated in the paper, to an accuracy of at least 3 parts in 1 000, the constant of the instrument depending upon the value accepted for the ratio c.

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(9) Influence of temperature.
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(1) INTRODUCTION.

The accurate measurement of many physical constants depends upon the precise determination of the high potentials used to produce electrical discharge. There is at present no accepted standard of measurement with which instruments employed for this purpose can be compared. The Kelvin attracted-disc electrometer type, for so long the most convenient means of high-voltage measurement, is not made to deal as an instrument of precision with the pressures now common in electrical practice; its size becomes prohibitive and its factor of safety is low. Pérot and Fabry* showed that it is suitable for the absolute measurement of low voltages, but for the direct measurement of high voltages there is need of a standard comparable in accuracy with the present standards of current and resistance and the low-voltage cell. Sphere spark-gap measurement of very high voltages is probably the nearest approach to it.

The theory of the electric field in such gaps has been fully worked out,† but the experimental means of checking observation against calculation still leaves much to be desired. A difference of 2 per cent is possible even in accurate sphere-gap high-voltage determinations, and it is necessary to take the mean of many readings to obtain a result reliable to 1 part in 1 000.

One convenient method of measuring high voltage indirectly is by finding the charging current of a condenser of special construction, and in that case the capacitance, current, and frequency have to be measured. Another method is by making part of a sphere gap an exploring area from which current is led to earth through rectifying valves and direct-current instruments. In these latter measurements the calculation of the capacitance of a condenser in electromagnetic measure requires the ratio c of the units. This is known to an accuracy of 1 part in 1 000 and the voltage measurements are

* *Comptes Rendus*, 1897, vol. 124, p. 180.
† A. RUSSELL: *Journal I.E.E.*, 1919, Supplement to vol. 57, p. 223.

limited to this accuracy of statement, though they may be made to a higher degree of certainty.

One method of measuring high potentials that has not hitherto been fully explored offers advantages within the above restriction. An ellipsoid suspended between plane vertical metallic surfaces at different potentials is polarized by the field and, if placed at an angle to it, experiences a torque which brings it into line. The magnitude of this torque can be calculated when the material and dimensions of the ellipsoid and the intensity of the undisturbed field are known, and can be observed either by static deflections or by allowing the suspended body to make small swings about a position of rest in line with the field.

Measurements made for the purpose of finding the dielectric constants of solid insulators have shown that this method is capable of high accuracy which depends largely on the perfection of form of the ellipsoids.* As

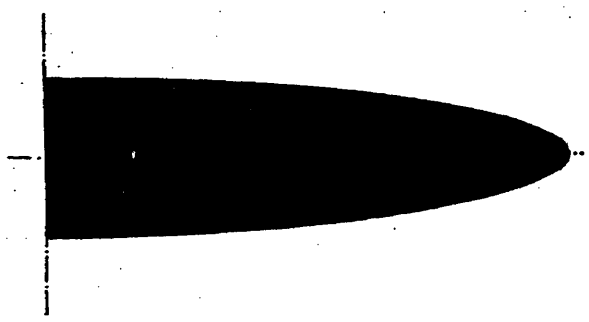


FIG. 1.—Enlarged image of ellipsoid.
Length = 3·9692 cm. Mass = 2·0496 grammes.
Diameter = 0·5970 cm. Moment of inertia = 1·65 g-cm².
Volume = 0·7388 cm³.

a matter of interest one of the ellipsoids in the above research was gilded and used to measure the intensity of the field. By a comparison of the value obtained with electromagnetic measurements of the voltage, values of c were found close enough to the accepted values to warrant a trial of the method as a means of measuring electric fields in electrostatic units.†

The method is only suitable for pressures high enough to maintain a field of several hundreds of volts per cm at the centre of the space between the plates, while at the same time the ratio of distance between plates to length of the ellipsoid should not be less than 25 if an accuracy above 1 in 1 000 is required. One advantage of such an instrument is that the calculations and working formulæ are simple and involve only the measurements of the dimensions of the ellipsoid and of its time of swing or deflection. The mechanical arrangement is also simple but, if it is to be used as a standard, the instrument must be large. In that to be described, for the measurement of voltages up to 200 000 with a desired accuracy of 1 in 1 000, the plates are 140 cm diameter and 100 cm apart.

The ellipsoids used in the previous work were made by Messrs. A. Hilger and Co. with such perfection that optical enlargement to 20 times or more the actual size failed to show a departure from the calculated ellipse of the same axial dimensions to as much as the thickness of a fine pencil line in an image 6 cm diameter and 40 cm long. It is the possibility of being able to rely on such workmanship that gives to the method, as it did to that of Pérot and Fabry, the first quality of an absolute standard instrument, an exact knowledge of the dimensions of the working part; in the present case this was a duralumin ellipsoid of revolution 0·59 cm diameter and 3·9 cm long (see Fig. 1).

* *Proceedings of the Royal Society*, A, 1909, vol. 82, p. 422.
† "A New Method of Measuring v," *Transactions of the University of Durham Philosophical Society*, 1908, vol. 3, p. 85.

(2) THEORY OF INSTRUMENT.*

The torque on the suspension of an insulated conducting ellipsoid, the longer axis of which makes an angle θ with the electric field F, is $B \sin\theta \cos\theta$, where $B = F^2V(L - N/LN)$, V is the volume of the body, and L and N are coefficients which depend only upon its shape. For a prolate ellipsoid of eccentricity e the longitudinal coefficient

$$N = 4\pi\left(\frac{1}{e^2} - 1\right)\left(\frac{1}{2e}\log\frac{1+e}{1-e} - 1\right)$$

and the transverse coefficient

$$L = 2\pi\left(\frac{1}{e^2} - \frac{1-e^2}{2e^3}\log\frac{1+e}{1-e}\right)$$

When the ellipsoid is held steadily in the position θ by torsion ϕ of the suspension the torque is a maximum at an angle of 45°. At smaller values of θ it is

$$2A\phi = B\sin 2\theta$$

$$= F^2V\frac{L-N}{LN}\cdot\sin 2\theta$$

or

$$F^2 = 2A\phi\frac{LN}{L-N}\cdot\frac{1}{V\sin 2\theta} \quad . \quad . \quad . \quad (1)$$

where A is found by experiment. The field is measured by observing the angle of torsion ϕ required to hold the ellipsoid steady at an angle θ to it.

When allowed to make small swings about the line of the field the motion of the ellipsoid is given by

$$\mathrm{I}\ddot{\theta} + A\theta + B\sin\theta\cos\theta = 0 \quad . \quad . \quad . \quad (2)$$

I being the moment of inertia about the axis of suspension.

A is then found from the free period T_0 with no field on, when B is zero and

$$T_0 = 2\pi\sqrt{\frac{\mathrm{I}}{A}}, \quad \text{or} \quad A = 4\pi^2n_0^2\mathrm{I} \quad . \quad . \quad (3)$$

n_0 being the number of free swings in a second.

For most of the work to be described the amplitude of swing was a few degrees and to a close approximation the equation of motion is

$$\mathrm{I}\ddot{\theta} + (A+B)\theta = 0 \quad . \quad . \quad . \quad . \quad (4)$$

The number of swings per second is then

$$n = \frac{1}{2\pi}\sqrt{\left(\frac{A+B}{\mathrm{I}}\right)}$$

$$A + B = 4\pi^2n^2\mathrm{I}$$

$$B = 4\pi^2(n^2 - n_0^2)\mathrm{I}$$

$$F^2 = \frac{B}{V}\cdot\frac{LN}{L-N} = 4\pi^2\frac{\mathrm{I}}{V}\cdot\frac{LN}{L-N}(n^2 - n_0^2)$$

* See *Proceedings of the Royal Society*, loc. cit., p. 422.

or $$F = k(n^2 - n_0^2)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where k (the constant of the instrument)

$$= 2\pi\left(\frac{\mathrm{I}}{V} \cdot \frac{LN}{L-N}\right)^{\frac{1}{2}}$$

For the measurement of high fields the difference between n and n_0 is so great that the latter may be neglected, and to an accuracy of 1 per cent the working formula is $F = kn$.

Swings of finite amplitude a modify the period, and the square of the frequency of swing reduced to an indefinitely small amplitude is

$$n_1^2 = \frac{n^2}{\frac{1}{2} + (\frac{1}{4} - \gamma\beta^{-2})^{\frac{1}{2}}} \cdot \left\{1 + \tfrac{1}{4} \cdot \frac{\frac{1}{2} - (\frac{1}{4} - \gamma\beta^{-2})}{\frac{1}{2} + (\frac{1}{4} - \gamma\beta^{-2})}\right\}^2 \quad (6)$$

or $$n_1^2 = n^2(1 + \tfrac{3}{2}\gamma\beta^{-2}) \text{ approx.}$$

in which $$\beta = 3\{(A/B) + 1\}$$

$$\gamma = 3\{(A/B)a^2 + \sin^2 a\}$$

The torque of the ellipsoid is proportional to the square of the field, and the instrument therefore gives true root-mean-square values. It is independent of the wave-form for pressures having the same R.M.S. value, and it is independent of temperature within possible ranges.

(3) The Ellipsoid.

In order that the difference $(n^2 - n_0^2)$ should be as large as possible in a given field the density of the ellipsoid should be small. Duralumin was used in preference to aluminium since it is more easily worked to a high finish and its density is nearly the same. No exact specification of size was given to Messrs. Hilger beyond the approximate dimensions, and the final measurements were 0·5970 cm diameter and 3·9694 cm long.

A platinum-iridium ellipsoid also made by Messrs. Hilger and measured at the National Physical Laboratory had a length of 2·4718 cm. This was enlarged optically to 26·5 cm and the duralumin ellipsoid when substituted for it gave an image of 42·55 cm. Its length deduced from these readings was (42·55/26·5) × 2·4718 = 3·9689. The mean of the two determinations, 3·9692 cm, was taken as its true length. The volume calculated from these figures, assuming true elliptical section, is 0·7408 cm³.

Measurements of the diameter of the ellipsoid along its axes gave the results compared in Table 1 with those calculated by taking the major axis 3·9692 and the minor 0·5970 and assuming that between these the section was truly elliptical.

Except at the tip the form is true to nearly 3 parts in 1 000. Higher accuracy is, of course, possible, but in ordering the ellipsoid the highest precision was not asked for. Fig. 2 shows a comparison between mathematical and actual form, the dimensions being enlarged many times.

The volume calculated from the observed form was 0·7388 cm³, which may be compared with that from the overall dimensions, viz. 0·7408 cm³.

Table 1.

Distance x from centre	Diameter		Ratio
	Observed	Calculated	
0	0·2985	0·2985	1·000
0·2799	0·2948	0·2954	0·999
0·5595	0·2844	0·2861	0·995
0·8397	0·2704	0·2704	1·000
1·1196	0·2453	0·2465	0·995
1·3995	0·2100	0·2114	0·998
1·6790	0·1577	0·1597	0·994
1·9593	0·0434	0·0515	0·840

An important factor determining the accuracy of the instrument is the moment of inertia of the ellipsoid. This was found from the geometrical moment of inertia and the density, which was obtained by careful weighing.

It was originally intended to suspend the ellipsoid in a rigid insulating saddle, but finally a hole was drilled through it and fitted with a tapered brass bush of density 8·44.

The change in the moment of inertia is

$$\pi\left(\frac{\rho_B - \rho_A}{10}\right)h[r_1^4 + r_2^4 + r_1^2 r_2^2 + r_1^3 r_2 + r_1 r_2^3]$$

The mass before bushing was 2·0496 grammes.
The final figures used were:—

Diameter:—0·5970 cm at 18° C.
Length:—3·9692 cm
Volume:—0·7388 cm³
Density:—2·7742
Original mass:—2·0496 grammes
Moment of inertia:—1·6509 g-cm² before bushing
1·6539 g-cm² after bushing

Table 2.

x	y_1	y_2	y	y^2	$a^2 - x^2$	$\frac{y^2}{a^2 - x^2}$
3	3·17	3·15	3·16	9·9856	443·6	0·02250
6	3·05	3·05	3·05	9·3025	416·6	0·02230
9	2·90	2·90	2·90	8·4100	371·6	0·02250
12	2·64	2·62	2·63	6·9164	308·6	0·02241
15	2·25	2·27	2·26	5·1076	227·6	0·02244
18	1·70	1·68	1·69	2·8561	128·6	0·02221
21	0·47	0·45	0·465	0·2139	11·6	0·01860

Ratio of enlargement = 10·72
Semi-major axis of enlarged image = 21·275 cm
Semi-minor axis of enlarged image = 3·2 cm
a^2 = 452·6 cm

The polarization coefficients L and N, the most important factors in the accuracy of the method, require the eccentricity e.

To determine this the enlarged image of the ellipsoid was divided into equal parts on either side of the centre and the ordinates were measured with as great accuracy as measurements on paper permit. y_1 and y_2 in Table 2 are on opposite sides of the axis.

regarded as the most probable value of e^2 to be us in calculating L and N.

Taking $e = 0{\cdot}9893$, $e^2 = 0{\cdot}9787$ and $e^3 = 0{\cdot}96$ the longitudinal coefficient $N = 0{\cdot}4489$, and the tra verse coefficient $L = 6{\cdot}0625$, whence

$$\sqrt{\left(\frac{LN}{L-N}\right)} = 0{\cdot}6967$$

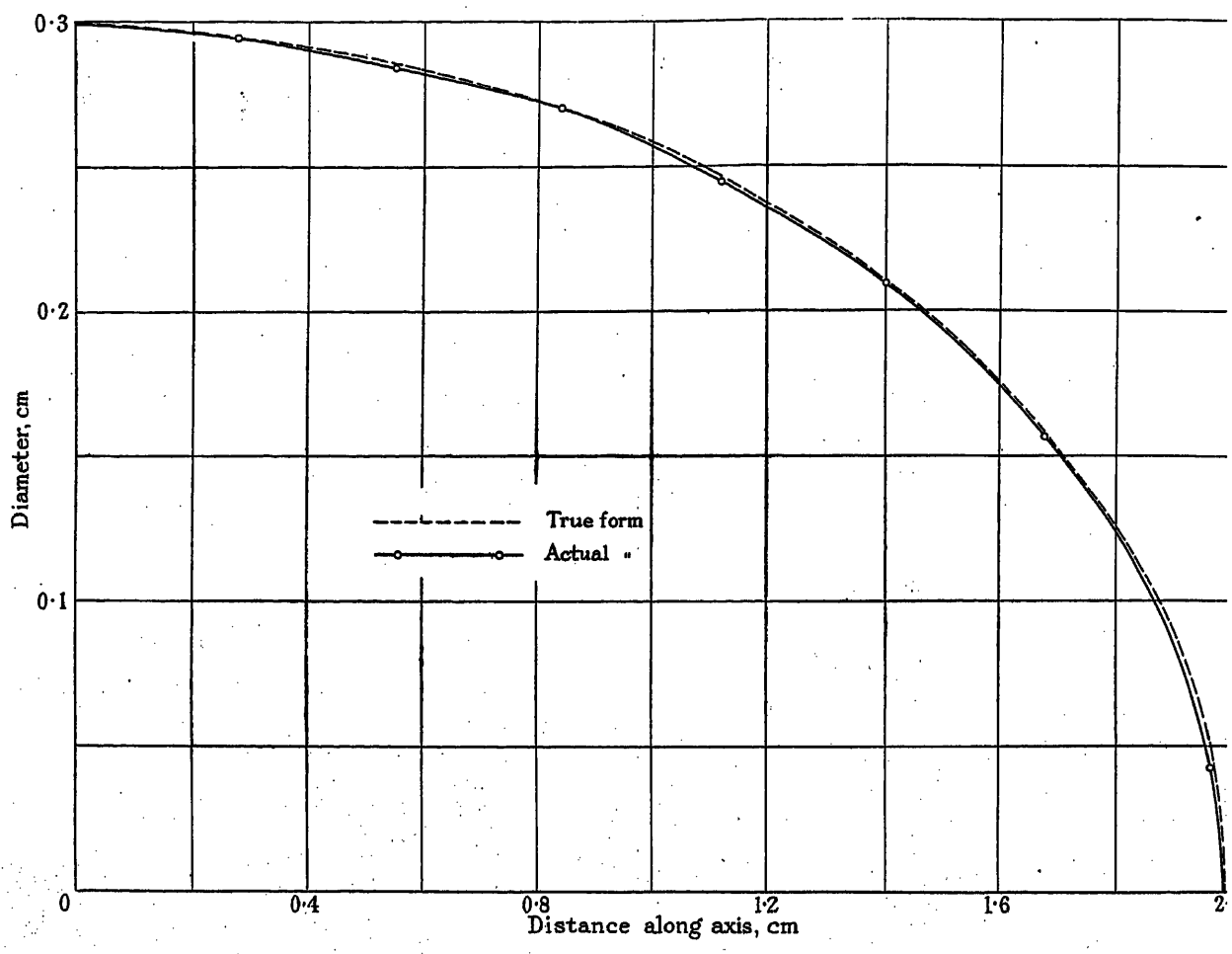


Fig. 2.—Comparison between actual and mathematical forms of the ellipsoid.

The differences between y_1 and y_2 as measured illustrate the difficulty of working from an enlargement, for by the method of shaping the ellipsoid they must be equal.

The average value of $e^2\left(=1-\frac{y^2}{a^2-x^2}\right)$ is $0{\cdot}97761$.

Omitting the last line in Table 2, $e^2 = 0{\cdot}97761$; including it, $e^2 = 0{\cdot}97914$.

The weights to be given to the readings are, however, not equal, for the torque is proportional to the product of charge on any ring element of the surface and its distance from the axis of suspension.

Weighting the values in this way, by taking moments about the axis, $e^2 = 0{\cdot}97872$.

The point of the ellipsoid plays so important a part in the concentration of the field that this may be

From the previous figures,

$$\sqrt{\frac{\mathbf{I}}{V}} = \sqrt{\frac{1{\cdot}6539}{0{\cdot}7388}} = 1{\cdot}4962$$

so that

$$F = 6{\cdot}2832 \times 1{\cdot}4962 \times 0{\cdot}6967(n^2-n_0^2)^{\frac{1}{2}}$$
$$= 6{\cdot}55(n^2-n_0^2)^{\frac{1}{2}} \text{ electrostatic units,}$$

Or, assuming $c = 3 \times 10^{10}$,

$$F = 1\ 965(n^2-n_0^2)^{\frac{1}{2}} \text{ volts per cm} \quad . \quad . \quad (1$$

Knowing from the spacing D of the plates and th tests applied that the field at the centre is uniform, th total applied voltage is FD.

(4) The Arrangement of Plates and Suspension.

The field between two flat parallel plates diverges at the edges in a manner that can be calculated or observed. When high voltages are used these edges are turned back to avoid brush discharge, for where this occurs the potential of the conductor may vary in a remarkable manner.* The spacing of the plates having been determined by trial (see Section 6) to give a negligibly small disturbance of the charge at the surface of the plate by that induced on the ellipsoid, the diameter was chosen to subtend an angle arc tan 70/50 at the centre.

The plates were made 140 cm diameter with $6\frac{1}{4}$ cm diameter rolled edges and spaced by gauge 100 cm

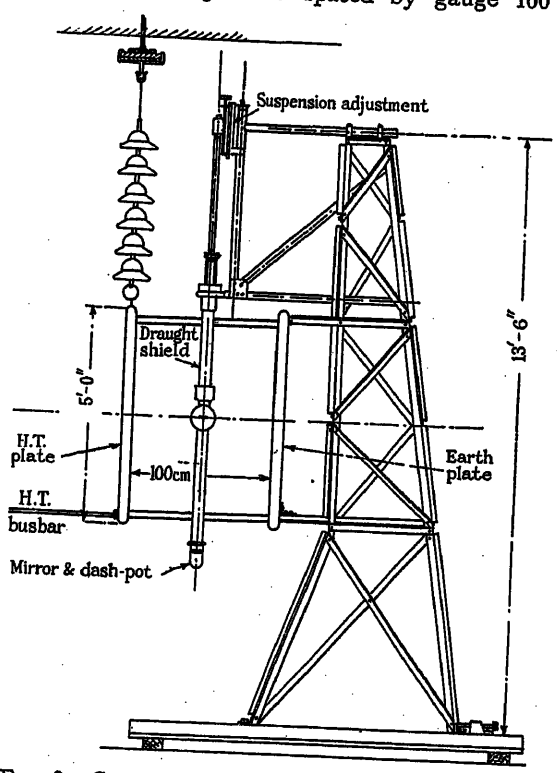


Fig. 3.—General arrangement of first form of ellipsoid voltmeter. Scale 1/53.

apart as a maximum. The distance could be varied by a screw adjustment from the foot supports and rails. Suspension-type insulators were at first used to hang the high-tension plate from an overhead girder, while the earth plate was supported on an iron lattice frame (see Fig. 3). Later the high-tension plate was supported from below and rigidly attached to the earth plate by bakelized paper tubes; the instrument could then be moved about the laboratory.

The most direct method of ascertaining the uniformity of the field between circular parallel plates is by experiment. A typical photograph of its distribution is given in *Wien-Harms Handbuch der Experimental Physik* (vol. 10, G. Hoffman: "Das Elektrostatische Feld," p. 41, Fig. 14). Several other references are quoted by him. Maxwell† gave a diagram of the spreading effect at the edges of two thin infinite parallel plates, but the only complete treatment of two parallel circular discs is that by Dr. J. W. S. Nicholson.* The problem is one of great mathematical complexity. The surface density on the inner side of the plates, of radius a, is there given by the expression for equal potentials

$$\sigma_2 = \frac{a}{4\pi}\sqrt{\left(\frac{\pi}{2}\right)}\int_0^\infty \lambda(1 - e^{-\lambda c})J_0(\lambda\rho)\phi(a\lambda)d\lambda \quad (q.v.)$$

Unfortunately this cannot be applied to discs with rolled edges, and at the present time there is no analytical solution of this most important practical problem. It might be solved by the superposition of the field between two toroids upon that of the parallel discs, but it would not be readily given a practical form.

Table 3.

Distance from centre-line	Time of 20 swings	n^2	$\sqrt{(n^2-n_0^2)}$	Ratio to field at centre
cm	secs.			
10	33·8	0·35	0·537	1·000
15	33·8	0·35	0·537	1·000
25	33·8	0·35	0·537	1·000
35	34·0	0·346	0·532	0·992
45	35·0	0·326	0·513	0·956
55	37·0	0·293	0·480	0·895
70	40·5	0·244	0·426	0·794

In order to examine the uniformity of the field between the plates in the present instrument a narrow metallic ellipsoid 1 cm long was suspended so that its oscillations could be counted when placed in various parts of the field. The results given in Table 3 are measurements taken in a plane midway between the plates, which are 140 cm diameter. The free period was 4·00 seconds per complete oscillation; $n_0^2 = 0{\cdot}0625$.

The field is therefore quite uniform over a diameter of 50 cm.

The details of the suspension of the ellipsoid and shield are given in Fig. 4.

As the ultimate aim was a steady deflection instrument of the mirror type, capable of reading over a wide range of voltage, special consideration was given to the suspension so as to ensure a permanent zero position and consistency of readings. The problem was complicated by the fact that no metal could be brought near the field of the instrument, and yet metal slides and screw feed were essential to the successful operation of the suspension control. Bakelized paper tubes, though flexible in themselves, gave the necessary rigidity when made up into a 5-bar frame (see Fig. 3). At the top of this frame, well out of the field, was mounted the adjusting gear consisting of a saddle sliding smoothly on steel guides, while from the bottom of the frame were suspended the draught tube and shield. For the steady deflection case the ellipsoid was hung by a bifilar suspension from a torsion head, the

* J. C. Maxwell: "Electricity and Magnetism," Art. 202, Fig. 12; or J. H. Jeans: "Mathematical Theory of Electricity and Magnetism," p. 328.
† "Electricity and Magnetism," vol. 1, par. 202, Fig. 12.

* *Philosophical Transactions of the Royal Society*, A, 1924, vol. 224, p. 303 (see p. 348).

sensitivity of the instrument being controlled by a clamp (Fig. 5) mounted on a piston sliding in the tube and actuated by the screw arrangement. When the clamp was lowered or raised the twistable length of

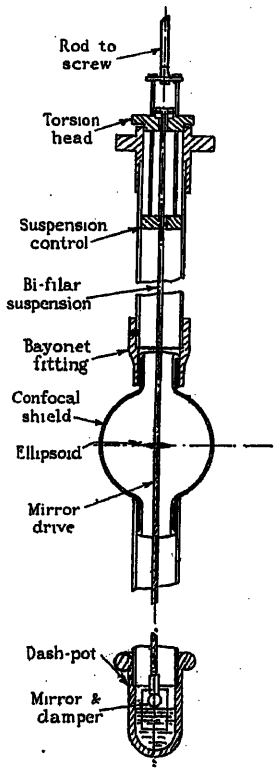


FIG. 4.

the thread was altered accordingly. This method was adopted in preference to moving the plates, for reasons which will be explained later.

When working by the method of steady deflections

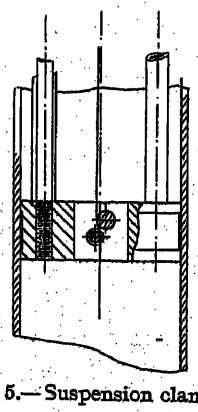


FIG. 5.—Suspension clamp.

the ellipsoid was fitted with a varnished conical paper tube which carried the mirror clear of the plates into a chamber containing a damping pot. This was made metallic to shield the mirror from the field. Attempts were made to use a metal suspension but it was found that a violent lateral oscillation occurred. Glass was also tried but, although mechanically strong enough under ordinary conditions, it was unable to withstand shock. Recourse was finally had to unspun silk, which has proved quite satisfactory.

(5) THE CALIBRATION OF THE TRANSFORMER VOLTAGE BY SPHERE SPARK-GAP.

Much work has been done under the direction of the International Electrotechnical Commission in connection with the standardization of the sphere spark-gap as a means of measuring high voltages. Curves of calibration have been published from time to time which give the distance at which a spark will pass between well-polished spheres of given sizes. Unfortunately these do not yet agree. Paschen's law has been verified over the whole range of gas pressure and temperature likely to be met with in practice, and sphere-gap measurements depend upon this for their consistency.

Measurement by spark discharge is not the most

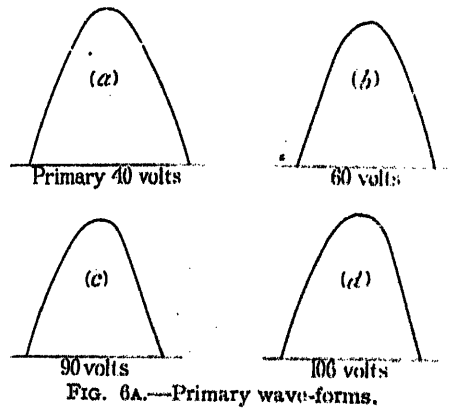


FIG. 6A.—Primary wave-forms.

satisfactory means of observing voltage in routine testing. It gives one point only and the effects of the discharge surge on apparatus connected across the gap may be disastrous. Since, however, the breakdown

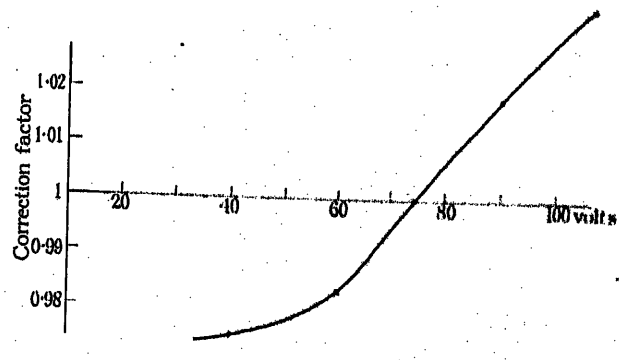


FIG. 6B.—Wave-form correction factor.

voltage does not greatly depend upon the size of the transformer used it is possible when calibrating a voltmeter by the sphere-gap, using a 2-kW transformer, to pass many sparks without the surface of the spheres being destroyed, though individual readings may differ by several per cent.

It is desirable for exact measurement that the applied

voltage should have a sine wave-form, and in the present case oscillograms were taken of the wave-form of the voltage obtained from a small high-speed motor-generator. Although the wave-form was not perfect it was free from ripples and gave consistent readings on the sphere spark-gap.

The spark-over value depends upon the maximum value of the voltage, and in order to compare the readings with those of the ellipsoid voltmeter, which records R.M.S. values, the wave-forms at various voltages were analysed from enlargements and their R.M.S. values calculated. It was then possible to correlate the ellipsoid voltmeter and the sphere-gap readings.

The wave-forms and the correction factors are shown in Figs. 6A and 6B. The change of wave-form is in this case small but not negligible; there is a third harmonic.

The agreement between our determinations of voltage and those of Whitehead and Castellain (*Journal I.E.E.*, 1931, vol. 69, p. 898) proves that the correction of sphere-gap readings for change of wave-form can be made with high accuracy, provided that many readings are taken and the mean values used.

The effect on the transformer of the capacitance load due to the voltmeter was examined, for it was evident that a slight rise of secondary voltage would occur at the closer spacings of the plates. Values of primary current with and without the voltmeter on the secondary are shown in Fig. 7.

The transformer ratio shown in Fig. 14 was found to be constant over the range 10 000–50 000 volts. The secondary voltage was determined by sphere spark-gap, while the primary voltage was measured to 1 part in 1 000 on a standard Weston instrument.

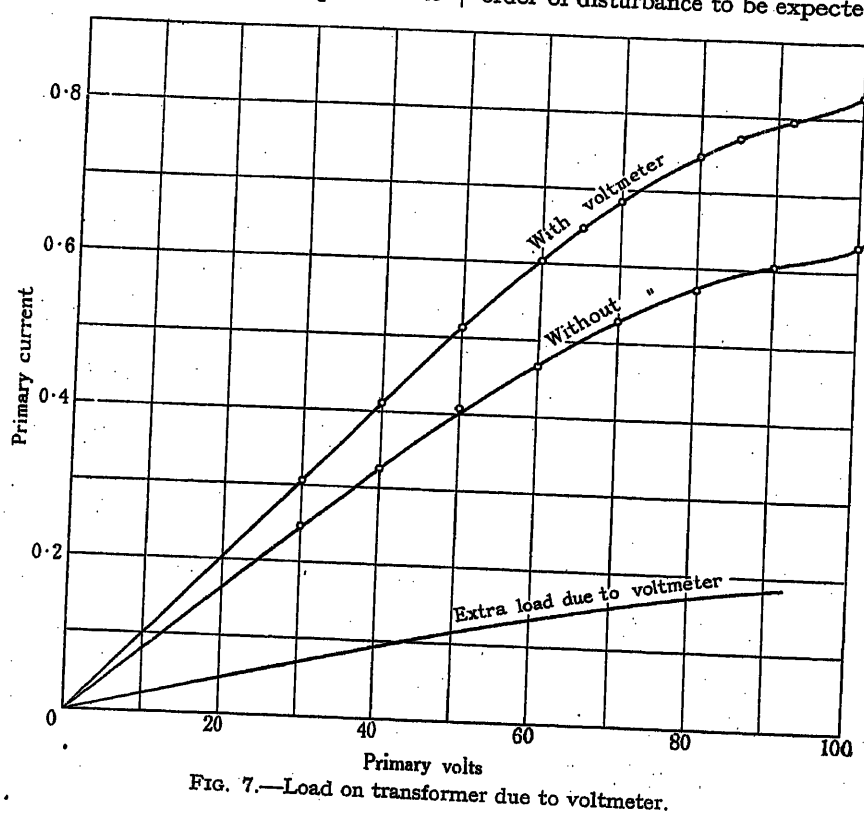


FIG. 7.—Load on transformer due to voltmeter.

(6) THE INFLUENCE OF THE SPACING OF THE PLATES.

It was thought that the charges induced on the ellipsoid might be sufficient to modify the distribution of charge on the pole-plates and have an appreciable influence on the torque.* The theory of this reaction in the case of a conducting ellipsoid making a finite angle with the field has not been worked out, but the following approximation when the two are in line indicates the order of disturbance to be expected.

The field X coinciding with the x axis, the charge on a ring element of radius y is

$$2\pi y\sigma ds = 2\pi y(X/N)\cos\theta\, ds,\dagger$$

where θ is the angle between the normal to the surface of the element and the direction of the field, N the longitudinal reaction coefficient, and ds an element of length of the boundary.

At the point of the ellipsoid $\sigma = X/N$, and $4\pi(X/N)$ is the intensity of field, corresponding to the intensity of uniform magnetization in an iron ellipsoid in a uniform magnetic field.

The charge dq on the element

$$= 2\pi y\frac{X}{N}\frac{dy}{ds}\cdot ds$$

$$q = \pi\frac{X}{N}y^2 = \frac{\pi X}{N}\left(1-\frac{x^2}{a^2}\right)b^2$$

* *Transactions of the University of Durham Philosophical Society*, 1908, vol. 3, p. 85.

† J. J. THOMSON: "Elements of the Mathematical Theory of Electricity and Magnetism," par. 166.

and the charge per unit length of the ellipsoid

$$q_1 = \frac{dq}{dx} = 2\pi\frac{X}{N}\cdot\frac{b^2}{a^2}x$$

The total charge on one half of the ellipsoid is

$$q = \left[\pi\frac{X}{N}y^2\right]_0^b = \frac{\pi b^2 X}{N}$$

Hence $q = 0{\cdot}625X$ electrostatic units of charge, the field being in electrostatic units.

This is the same as the charge on a parallel-plate condenser with the plates having 0·78 cm² area placed 1 mm apart, and is very small compared with that on the pole-plates charged to the same gradient. At 50 cm apart the induced charge on one end of the ellipsoid is 1/28 000 of that on the plates.

Consider the forces on a ring element distant x from the vertical axis and carrying a charge δq (Fig. 8).

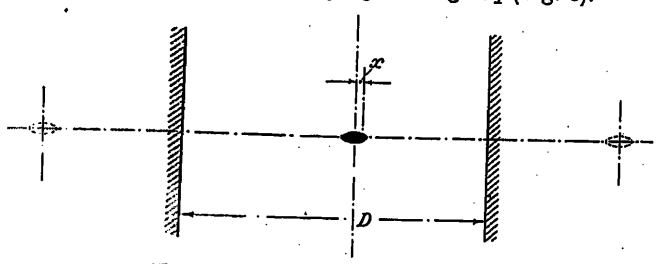


FIG. 8.—Ellipsoid and images.

These forces are:—

(1) An attraction $(\delta q)^2/(4x^2)$ between elements of opposite polarity on the surface of the ellipsoid, and directed towards the centre.

(2) An attraction $(\delta q)^2/(D-2x)^2$ to the opposite image in the nearest plate, and away from the centre.

(3) An attraction towards the centre $(\delta q)^2/(D+2x)^2$ to the image in the far plate.

The total force towards the centre on the element is

$$(\delta q)^2\left\{\frac{1}{4x^2}+\frac{1}{(D+2x)^2}-\frac{1}{(D-2x)^2}\right\}$$

and is less than in an infinite uniform field.

The force separating the charges on the surface is therefore greater than in a perfectly uniform field with no pole-plates present. Writing the equivalent field added by the reaction as X_1 we have

(*a*) If there were no reaction (and X_1 then zero)

$$X_0(\delta q) = \frac{(\delta q)^2}{4x^2}$$

the attraction of the separated charges being in equilibrium with the influence of the initial applied field X_0.

(*b*) The *added* force in the x direction

$$X_1\delta q = (\delta q)^2\left[\frac{1}{(D-2x)^2}-\frac{1}{(D+2x)^2}\right] = \frac{8Dx(\delta q)^2}{(D^2-4x^2)^2}$$

or X_1 (the force on unit charge) $= \int\frac{8Dx}{(D^2-4x^2)^2}dq$

Writing $q_1 = mx$, where $m = 2\pi(X_0/N)(b^2/a^2)$, the resultant field on the ellipsoid due to the summation of forces over the surface superposed on the original field is then

$$X_1 = X_0\left\{1+\int_0^a 2\pi\frac{X}{N}\cdot\frac{b^2}{a^2}\cdot\frac{8Dx^2dx}{(D^2-4x^2)^2}\right\}$$

The ratio a/D was varied during the experiment from 0·25 to 0·04, the latter being the working value. The fourth power of this is negligible for the present purpose and we take

$$X_1 = X_0\left\{1+k\int_0^a\frac{x^2dx}{1-(x^2/p^2)}\right\}$$

where $k = \frac{16\pi b^2}{D^3a^2}\cdot\frac{X_0}{N}$, $p = \frac{D}{\sqrt{8}}$.

Thus $\frac{X_1}{X_0} = 1+k\left(\frac{1}{\sqrt{8}}\log\frac{D+a\sqrt{8}}{D-a\sqrt{8}}-\frac{2a}{D}\right)$

Writing the last two terms as C we have

$$X_1 = X_0(1+C)$$

The influence of the reaction of the charges induced on the ellipsoid by the field upon the distribution of charge on the pole-plates is to increase the initial field X_0 at the ellipsoid by an amount CX_0, making the total field as a first approximation $X_1 = X_0 + CX_0$. The charges on the ellipsoid are therefore increased in this proportion and these added charges give as a second approximation

$$X_2 = X_0 + CX_1' = X_0 + CX_0(1+C) = X_0\{1+C(1+C)\}$$

The next approximation gives $X_3 = X_0 + CX_2$, and by the well-known method of successive images the final field

$$X = X_0\{1+C(1+C(1+C\ldots\}$$
$$X = X_0\{1+C+C^2+C^3+C^4\ldots\}$$

that is $X = X_0/(1-C)$.

This may be written $X = X_0/(1-fX_0)$, where f is a constant depending on the intensity of the field. Since f is very small, $X = X_0 + fX_0^2$ is a close approximation to the resultant field.

The value of a is 1·9845 cm, $\sqrt{8} = 2{\cdot}828$, $a\sqrt{8} = 5{\cdot}613$. The values of X and the resultant increase of field for different spacings D are given in Table 4.

TABLE 4.

Voltage between Plates = 50 kV.

D	X_0 (electrostatic units)	f	fX_0	Percentage increase of field
cm				
25	6·66̇	0·000457	0·003046	0·3046
50	3·33̇	0·000048	0·00016	0·016
75	2·22̇	0·000019	0·000042	0·00422
100	1·66̇	0·000010	0·0000166	0·00166

The observed results are shown in Fig. 9.

The maximum difference between calculated and observed values is 2½ per cent, much too great to be accounted for by a concentration of charge on the plates induced by that on the ellipsoid.

The values of the field intensity *at the points of the ellipsoid* are greater in the ratio

$$4\pi/N = 12{\cdot}56/0{\cdot}4489 = 28$$

times that of the undisturbed field. Taking the spacing at which the difference in Fig. 9 is a maximum and begins to decrease, as 55 cm, and the applied field as 44 000 volts, or 800 volts per cm, the maximum concentration at the end of the major axis gives a field of 22 400 volts per cm (R.M.S.) or 32 000 crest value. This is very near to the known breakdown strength of air and there can be little doubt that at this spacing and voltage the ellipsoid can no longer hold its induced charge. At the lowest spacings (15 cm) and with this voltage a luminous glow appears at the ends, and at the intermediate spacings and with gradients from 400 to 800 volts per cm, that is with gradients at the point from 11 200 volts per cm and upwards, there are certainly ions formed by collision at atmospheric pressure.

Until the point is reached when the ellipsoid begins to lose its charge its motion is a regular function of the field strength.

The increase in secondary voltage due to the added capacitance of the voltmeter can be determined by calibrating the transformer with and without the voltmeter connected, as shown in Fig. 7.

Assuming as a first approximation that the capacitance current of the voltmeter is inversely proportional to the distance between plates, it is found that the calculated rise in voltage, due to capacitive reactance, above that observed with the 100-cm spacing, agrees substantially with that obtained experimentally (see Table 5).

It is clear that when a small transformer (2 kV) is used the rise of its secondary terminal voltage due to capacitive reactance is a greater cause of possible error than the reaction of the ellipsoids on the pole-plates, but by working at spacings of 100 cm the effects are both extremely small.

As a test of whether any electric wind could be observed from the point of the ellipsoid, smoke from a heap of burning waste was allowed to pass between the plates with the field on, but no trace of streaming near the ellipsoid, such as that observed from a pointed earthed electrode, could be seen.

(7) The Wind Shield.

The previous experiments had all been carried out by the method of swings and with the ellipsoid suspended freely between the plates with no wind shield in use. This, though possible in a room free from air currents, is not suitable for use in test-rooms where there is continuous movement, unless strong fields are used.

In order to protect the ellipsoid and suspension from draughts it was enclosed in a long bakelite tube. The determination of the shielding effect involves a knowledge of the dielectric constant of the shield; this was obtained by converting the tube into a cylindrical condenser.

A long sheet of copper foil was placed in the bakelite tube and rammed tight with cotton waste, while a

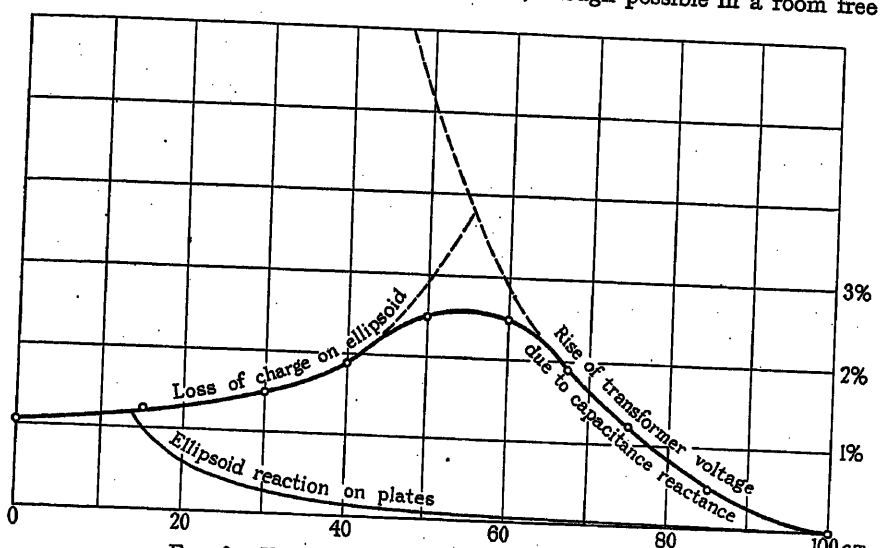


Fig. 9.—Variation of voltmeter reading, with spacing.

Table 5.

Open-circuit voltage = 39·4 kV.

Spacing	Reactance voltage	Terminal voltage	Per cent increase	Observed increase
cm	volts	volts		per cent
100	7 080	40 000	0	0
90	7 840	40 140	0·35	0·25
80	8 850	40 350	0·87	0·76
70	10 100	40 680	1·70	1·65
60	11 800	41 110	2·77	2·8

similar piece of foil was bound tightly around the outside. The capacitance was then determined by comparison with a standard condenser by the ballistic method.

Capacitance of standard	$= 0{\cdot}025\ \mu F$
Mean deflection	$= 17{\cdot}0$ divisions
Mean deflection of cylinder	$= 2{\cdot}9$ divisions
Capacitance	$= 0{\cdot}00235\ \mu F$
Length	$= 59$ in.
Thickness	$= 0{\cdot}125$ in.
Internal diameter	$= 2$ in.

the value of the field inside the tube as 75 per cent of the external field, from which it was concluded that the two-dimensional case was not a sufficiently good approximation to use.

The refraction of the vertical component of the three-dimensional field does not lend itself to exact determination. The tube was therefore cut into two parts and cemented to a spherical Pyrex glass vessel set concentric with the ellipsoid.

The radius of this vessel was chosen to be 6·7 cm, for at this value the shell conforms very nearly to an equipotential surface confocal with the ellipsoid.

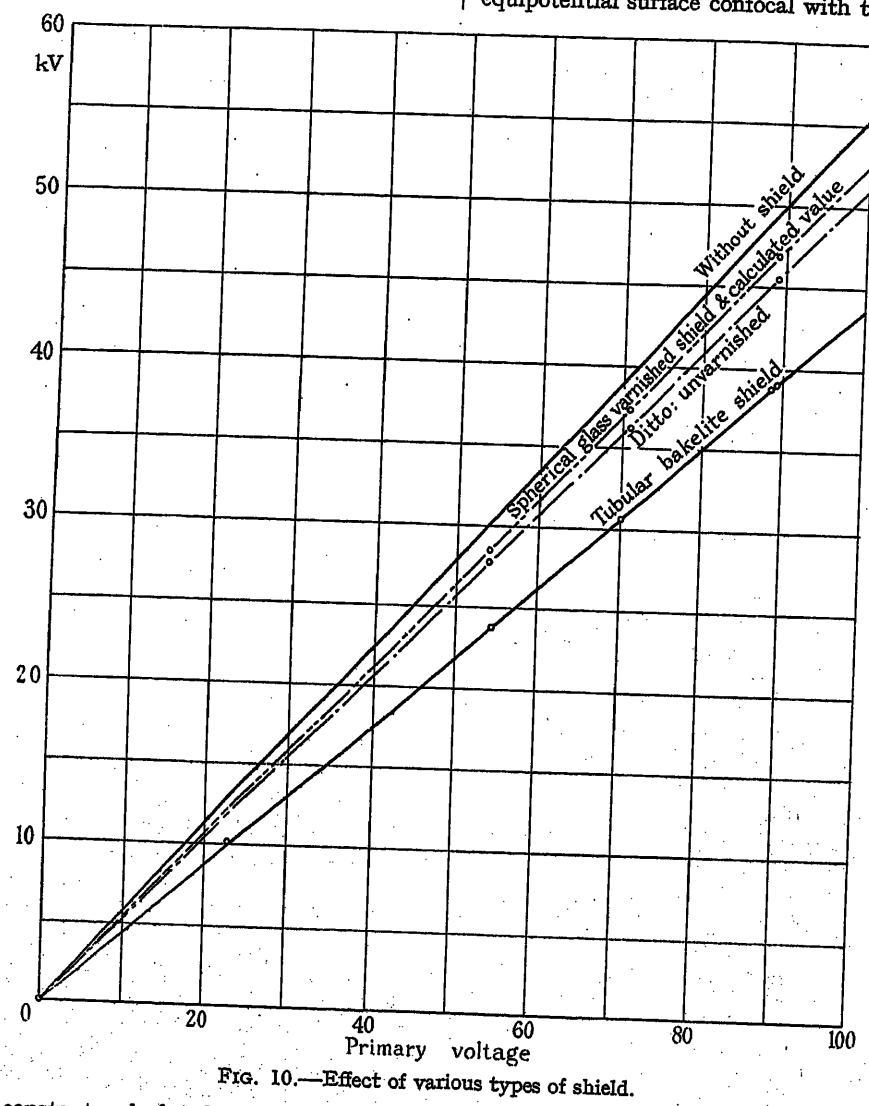


FIG. 10.—Effect of various types of shield.

The dielectric constant calculated from these data is 3·5.

The theory of shielding for the cylindrical case is given by du Bois,* and applying his method the value of the field strength inside the tube was found to be 92 per cent of the original field.

To check this the ellipsoid was suspended inside the tube and its oscillations were observed in a mirror, a beam of light being projected up the tube. This gave

* *Electrician*, 1897–8, vol. 40, p. 816.

The theory of shielding by a spherical magnetic shell as given by du Bois is at once applicable in the present case by substituting for μ in his expressions the known value of the dielectric constant κ for the material of the shell. Taking the ratio of the original field to that when the shell is present as g, du Bois's expression is

$$g = 1 + \frac{2}{9}\frac{(\kappa - 1)^2}{\kappa}(1 - p_1)$$

where $p_1 = (r/r')^3$, r being the inner and r' the outer

radius. In our case $r' = 3{\cdot}2$ in., $r = 3{\cdot}1$ and $\kappa = 4{\cdot}48$ for Pyrex glass.

Thus $$g_1 = 1 + \frac{2}{9} \cdot \frac{3{\cdot}48^2}{4{\cdot}48}\left\{1 - \left(\frac{3{\cdot}1}{3{\cdot}2}\right)^3\right\}$$
$$= 1{\cdot}054$$

so that the field is reduced by shielding, in the calculated ratio $1/g_1 = 0{\cdot}9485$.

The first measurement of the field within the vessel, made by the method of swings, gave $1/g = 0{\cdot}9220$, a difference of 2 per cent. A possible source of this shielding error was moisture on the glass vessel, and to remedy this the shield was coated with non-hygroscopic varnish. An immediate improvement was apparent and on repeating the experiment $1/g = 0{\cdot}9466$, a difference of $0{\cdot}2$ per cent. The means of the results are shown in Table 6 and plotted in Fig. 10.

Thus whenever it is advisable or necessary to enclose the ellipsoid, the field within the spherical enclosure can be readily found to this order of accuracy, a quarter of 1 per cent.

TABLE 6.

Condition	Primary voltage	Period	Apparent field	Real field	Values of $1/g$ after shielding
	volts	secs.			per cent
Unvarnished flask	89	4·3	45·7	49·5	92·2
Varnished flask	89	4·2	46·8	49·5	94·66
	71	3·36	37·5	39·6	94·7
	54	2·56	28·5	30·2	94·5

(8) THE INFLUENCE OF AIR PRESSURE.

The total enclosure of the suspension made it possible to examine the influence of gas pressure.

This investigation was considered necessary, for, although the change of dielectric constant of air due to variations of atmospheric pressure is negligibly small in its influence, the changes in the conducting state of air in an electric field as the pressure is lowered are well known.

The experiment was carried out by keeping the voltage across the plates constant and measuring the change in the period of oscillation as the air pressure was lowered. From atmospheric pressure down to 30 cm of mercury the period was very nearly constant (see Fig. 11), but at this point the period of the swings began to be longer and it was recognized that the air within the vessel was no longer in the same electrical condition. The torque on the ellipsoid was much less than before; the space around it had become conducting and acted as a shunt or shield to the ellipsoid.

There is no other explanation of the loss of torque except that the ellipsoid could no longer hold its charge steadily, the gradient at its point being 11 000 volts per cm, and the value X/p (volts per cm per mm pressure) being 37.

There would undoubtedly be a discharge from the point of the ellipsoid before this pressure was reached, for the radius of curvature may be taken as about 1 mm. But at the pressure of 30 cm the rate of recombination or absorption of ions as the field is reversed is not in equilibrium with the discharge, and the space becomes ionized, forming a conducting medium after the manner of the Heaviside layer.

The field inside a homogeneous sphere of dielectric constant ϵ placed in a uniform field F is less than the undisturbed field* in the ratio $\frac{3}{\kappa + 2}$. If the observed field is F_1 the apparent dielectric constant $\kappa = \left(3\frac{F}{F_1} - 2\right)$. Since F is inversely proportional to the period of swing, $\kappa = \left(3\frac{T_1}{T} - 2\right)$, T being here the period at atmospheric pressure, T_1 at the lower pressure. This relation between κ and T_1 is linear and is a very sensitive means of measuring change of gas pressure within a closed glass vessel in which a metallic ellipsoid can be suspended and to which an external electric field can be applied.

The apparent dielectric constant of an ionized vapour

TABLE 7.

Air pressure	Period	n	n/N
	secs.		
750	1·9	0	0
450	1·95	$1{\cdot}04 \times 10^{11}$	$2{\cdot}5 \times 10^{-13}$
250	2·00	$4{\cdot}95 \times 10^{11}$	$2{\cdot}1 \times 10^{-12}$
200	2·03	$8{\cdot}71 \times 10^{11}$	$4{\cdot}6 \times 10^{-12}$
150	2·07	$14{\cdot}4 \times 10^{11}$	$10{\cdot}3 \times 10^{-12}$
100	2·42	$1{\cdot}35 \times 10^{12}$	$1{\cdot}45 \times 10^{-11}$
50	3·40	$1{\cdot}04 \times 10^{14}$	$2{\cdot}34 \times 10^{-9}$
20	4·70	$3{\cdot}96 \times 10^{14}$	$2{\cdot}13 \times 10^{-8}$
10	6·0	$8{\cdot}32 \times 10^{14}$	$8{\cdot}95 \times 10^{-8}$
5	7·9	$18{\cdot}3 \times 10^{14}$	$3{\cdot}95 \times 10^{-7}$

exposed to a maximum value F_0 electrostatic units per cm between plates a distance D apart is†

$$\kappa = 1 + \left(\frac{4\pi ne}{F_0}\right)^{\frac{1}{2}}$$

where n is the number of ions per cm^3 and e here the ionic charge.

* J. H. JEANS: "The Mathematical Theory of Electricity and Magnetism," p. 225.
† H. A. WILSON: "The Electrical Properties of Flames," p. 109.

Hence in unit space, with $D = 1$,

$$n = \frac{9}{4\pi}\left(\frac{T_1}{T} - 1\right)^2 \frac{F_0}{e}$$

$$= 45{\cdot}0 \times 10^{10} X_0 \left(\frac{T_1}{T} - 1\right)^2 \text{ ions per cm}^3$$

X_0 being in volts per cm.

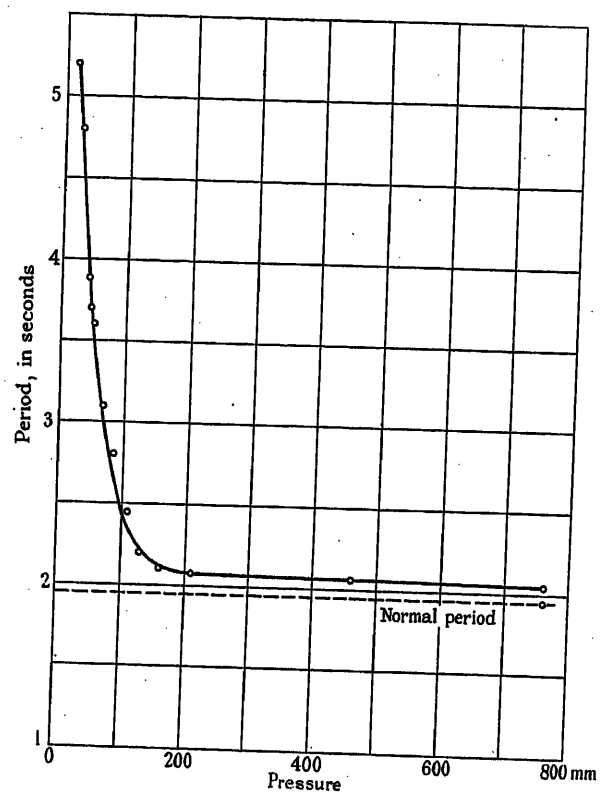


FIG. 11.—Effect of pressure.

With 40 000 volts between the plates 100 cm apart $X_0 = 400$, and some of the observed values of T and calculated values of n are given in Table 7.

TABLE 8.

p	n	$\log_e (n_2/n_1)$	$p_1 - p_2$	$\frac{\log_e (n_2/n_1)}{p_1 - p_2}$
150	$14{\cdot}4 \times 10^{11}$	—	—	—
125	$45{\cdot}7 \times 10^{11}$	0·5015	25	0·0200
100	$135{\cdot}5 \times 10^{11}$	0·4720	25	0·0188
90	213×10^{11}	0·1965	10	0·0196
80	322×10^{11}	0·1795	10	0·0179
70	504×10^{11}	0·1945	10	0·0194
60	726×10^{11}	0·1575	10	0·0157
50	$1\,040 \times 10^{11}$	0·1561	10	0·0156
40	$1\,635 \times 10^{11}$	0·1955	10	0·0195
30	$2\,340 \times 10^{11}$	0·1557	10	0·0155
20	$3\,960 \times 10^{11}$	0·2285	10	0·0228

The ratio n/N is that of the number of ions present to the molecules of gas per cm³.

Hence, although the number of ions present is exceedingly small compared with the total number of molecules, this small number is sufficient to exercise a marked shielding influence.

The curve of Fig. 11 is logarithmic except at the start and finish, which are rather indeterminate.

Writing $\log (n_2/n_1) = k(p_1 - p_2)$ we get the figures in Table 8.

Thus the rate of increase in the ionic content of the flask as the pressure is lowered, the external electric field being constant throughout, is nearly logarithmic over the greater part of the range, within the limits of experimental error.

(9) THE INFLUENCE OF TEMPERATURE.

The field is proportional to

$$\left[\frac{\mathbf{I}}{V}\left(\frac{LN}{L-N}\right)\{n^2 - n_0^2\}\right]^{\frac{1}{2}}$$

in which the ratio $LN/(L - N)$ is independent of temperature range, so that

$$\frac{\mathbf{I}}{V} = \frac{3m}{20} \cdot \frac{2 - e^2}{1 - e^2} \cdot \frac{1}{a(1 + a\theta)}$$

in which a is the coefficient of linear expansion and θ the change of temperature from normal, m the mass and e the eccentricity,

Thus $\sqrt{(\mathbf{I}/V)}$ is proportional to $1 - \frac{1}{2}a\theta$, neglecting higher powers. $a = 24 \times 10^{-6}$, hence

$$F = F_0\left\{1 - \frac{12}{10^6}(\theta - \theta_0)\right\}$$

which gives a difference of 0·0082 per cent per degree.

For a range of 10 degrees C. in room temperature the difference is 0·012 per cent, which is beyond the limit aimed at in the present work.

Both n^2 and n_0^2 vary inversely as the moment of inertia, and n^2 directly as the volume.

n_0 can be made as small as possible by the choice of suspension, and the change of volume of the ellipsoid with temperature can be regarded as having a negligibly small influence on the measurements.

(10) EXPERIMENTAL RESULTS.

The method of procedure when dealing with the oscillating ellipsoid was to set the primary voltage to give a certain sphere-gap voltage on the secondary and to observe the times of a number of small swings of the ellipsoid. It was found convenient to project a beam from an arc lamp on to the side of the swinging body so that a point of light, due to the convex mirror effect, ran along its polished surface with each swing.

The swings were timed by the method of Gauss with a stop-watch chronometer which was standardized in the building by a seconds pendulum controlled from Greenwich and did not vary more than a few seconds per day.

The duration of each set of swings depended on the field strength and, the damping being small, it was

possible to measure, in successive trials, periods agreeing to 1 part in 1 000.

The observations given in Table 9 are typical of the many made.

The last column is the ratio of the potential difference between the plates, expressed in volts, to that in electrostatic units. The mean value is 299·97.

From the results for the different spacings the derived curves shown in Fig. 9 were obtained.

slows down with the appearance of corona. Raising the voltage still further causes the ellipsoid to sway backwards and forwards between the plates. This effect occurs in a field of 2 400 volts per cm, and indicates the upper limit possible for the given ellipsoid.

TABLE 9.

Spacing 100 cm; free period 100 secs.

Primary volts (R.M.S.)	Sphere-gap volts V_s on secondary	Number of swings	Duration	Period	$\sqrt{(n^2-n_0^2)}$	F (electrostatic units)	$F \times D$	V_s/FD
89·8	50 000	20	79·5	3·975	0·255	1·669	166·900	299·58
89·52	49 800	20	79·0	3·950	0·2535	1·658	165·800	300·2
72·1	40 500	20	97·0	4·850	0·2061	1·350	135·000	300·0
70·35	39 500	20	99·8	4·990	0·2001	1·310	131·000	301·5
53·4	30 100	10	64·9	6·490	0·1540	1·008	100·800	298·6
53·2	29 900	10	65·25	6·525	0·1532	1·003	100·300	298·0
35·6	20 100	10	97·0	9·700	0·1031	0·673	67·300	298·9
35·8	20 200	10	97·4	9·740	0·1025	0·675	67·500	299·0

It is essential that the earth plate be earthed by a cable properly bonded to it.

In the case of the steady-deflection type of instrument its absolute calibration requires a knowledge of the torsion constant for the suspension. This can be obtained by an oscillation method and a value of the moment of inertia of the moving parts; alternatively a

TABLE 10.

Suspension 70 cm; initial angle 45°, without shield.

kV	V^2	2ϕ	$\sin 2\theta$	$V^2 \sin 2\theta$	$\frac{V^2 \sin 2\theta}{2\phi}$
66·0	4 356 × 10^6	15·6°	0·9837	4196·0 × 10^6	2·69 × 10^8
60·0	3 600 × 10^6	13·0°	0·9744	3507·8 × 10^6	2·70 × 10^8
50·0	2 500 × 10^6	9·1°	0·9784	2446·0 × 10^6	2·69 × 10^8
40·0	1 600 × 10^6	5·9°	0·9947	1591·52 × 10^6	2·70 × 10^8
30·0	900 × 10^6	3·4°	0·9982	909·38 × 10^6	2·67 × 10^8
20·0	400 × 10^6	1·6°	0·9996	399·84 × 10^6	2·50 × 10^8
10·0	100 × 10^6	0·4°	0·9999	99·99 × 10^6	2·50 × 10^8

TABLE 11.

Suspension 70 cm; initial angle 45°, with shield.

kV	V^2	2ϕ	$\sin 2\theta$	$V^2 \sin 2\theta$	$\frac{V^2 \sin 2\theta}{2\phi}$
66·7	4 449 × 10^6	14·0°	0·9703	4 217 × 10^6	3·07 × 10^8
60·0	3 600 × 10^6	11·5°	0·9799	3 530 × 10^6	3·06 × 10^8
50·0	2 500 × 10^6	8·10°	0·9900	2 475 × 10^6	3·06 × 10^8
40·0	1 600 × 10^6	5·20°	0·9960	1 592 × 10^6	3·06 × 10^8
30·0	900 × 10^6	2·92°	0·9987	897 × 10^6	3·07 × 10^8
20·0	400 × 10^6	1·30°	0·9997	399·9 × 10^6	3·06 × 10^8
10·0	100 × 10^6	0·33°	0·9997	99·97 × 10^6	3·03 × 10^8 (Mean 3·063 × 10^8)

It will be seen that for accurate results the spacing must be of the order of 100 cm. At a close spacing of 15 cm the ellipsoid has a tendency to instability and

known torque could be applied to the suspension by mechanical or electromagnetic means.

A more direct method of approach is to accept the calibration of the transformer by the oscillation instrument and from a knowledge of the applied field and the resultant deflections to derive the torsion constant, the values of which should be consistent among themselves for the proper working of the instrument.

The equation is

$$A\phi + B \sin\theta \cos\theta = 0$$

$$A = -\frac{B \sin 2\theta}{2\phi} = \frac{bV^2 \sin 2\theta}{2\phi}$$

where θ is the angle which the axis of the ellipsoid makes with the field, ϕ is the torsion angle, and B the polarization constant. By means of the suspension adjustment the voltmeter can be arranged to give any desired range of scale reading for a given voltage variation. The zero of the instrument was found by setting the ellipsoid in such a position that applying a voltage gave no deflection. As a trial an initial angle of 45° was given to the ellipsoid and a series of readings were taken with and without the wind shield. The results are shown in Tables 10 and 11 and plotted in Fig. 12.

The marked advantage of the shield in the steady-deflection method is shown by the fact that the points all lie actually on the curve and by the greater consistency of the values of the torsion constant.

An analysis of the figures in the last column, neglecting the value 10 kV which is really below the range of the instrument, shows a deviation from the mean of 1 part in 300, so that individual results can be relied on to 0·33 per cent. The readings were taken on a circular scale of 5 ft. radius and could be read to 0·01 degree.

From the data already obtained the actual scale form can be determined by extrapolation. Fig. 13 shows the scale to be of a modified square-law type, tending towards saturation at the higher voltages when the ellipsoid pulls into line with the field.

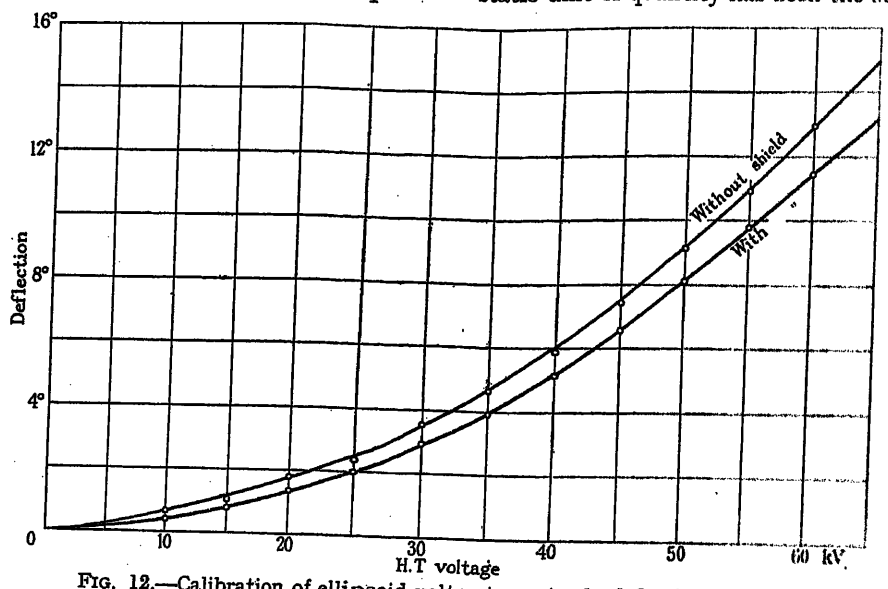


FIG. 12.—Calibration of ellipsoid voltmeter—steady-deflection type.
Initial angle 45°. Suspension 70 cm.

(11) DETERMINATION OF RATIO OF UNITS.

The ratio c of the electromagnetic unit to the electrostatic unit of quantity has been the subject of a number of careful determinations both optical and electrical. Although the experiments have been carried out by the highest authorities the collected results show a deviation of about 1 per cent on either side of their mean. The ellipsoid voltmeter offers a simple and direct method of determining the ratio of the units at low frequencies.

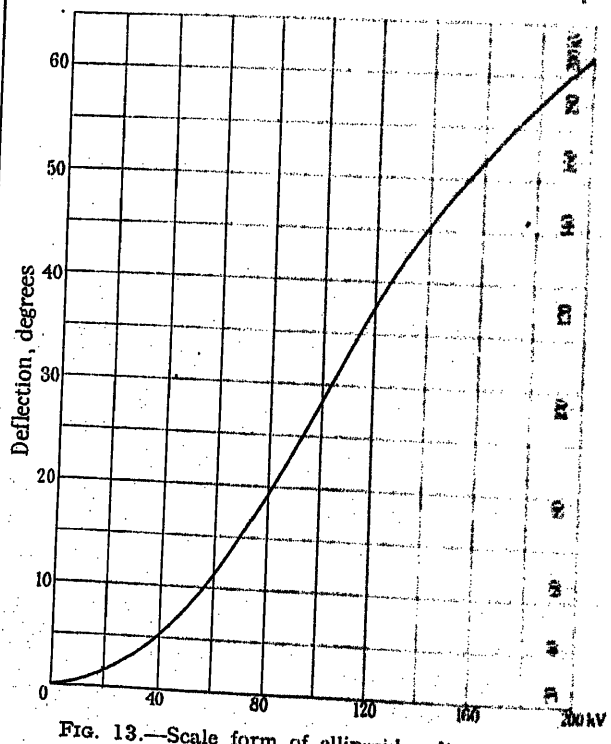


FIG. 13.—Scale form of ellipsoid voltmeter for 0–200 000 volts.

In the determination of the electrostatic quantities no difficulty is experienced in obtaining a reasonable order of accuracy. On the electromagnetic side the problem is not so simple, involving as it does the measurement of the voltage across the plates. This could be done by a capacitance method, but the recent researches carried out by the British Electrical and Allied Industries Research Association on sphere-gaps suggest that, by careful operation under the conditions laid down, results accurate to 0·2 per cent can be obtained.

Thus we have available a method of comparison which, though not absolutely precise in its elements, yet allows a large number of determinations to be easily made, leading to a final average result of a high degree of probability.

As mentioned in Section (5), the transformer was calibrated carefully with a sphere spark-gap, temperature and pressure corrections being rigorously applied, and the new E.R.A. values, which have had striking confirmation in connection with corona work in this laboratory, were used (see Fig. 14).

The mean of the readings in the last column of Table 9, the observations in which were taken without the express intention of determining c, gives the number of volts in 1 electrostatic unit of pressure as determined by this instrument. This corresponds to a value of c of $2{\cdot}995 \times 10^{10}$ cm per sec., which must be divided by the reaction coefficient 1·000016, corresponding to the spacing used, giving $2{\cdot}995 \times 10^{10}$ as a final value.

The voltages given by Whitehead and Castellain for sphere-gap calibration are international units, while those determined by the ellipsoid voltmeter are in C.G.S. units. To express their ratio when both are in C.G.S. units the figures of the last column in Table 9 must be multiplied by $1{\cdot}0004_9$, the ratio of the international to the C.G.S. value. This gives for the ratio c $2{\cdot}996_8 \times 10^{10}$, the subscript figure being retained to indicate the direction of change.

The mean of the best previous measurements is given by Abraham as 3·0001 and by Sir F. E. Smith as 2·998 to 1 part in 3 000.

By isolating the centre portion of the earthed plate another method of measuring c is obtained which is under investigation.

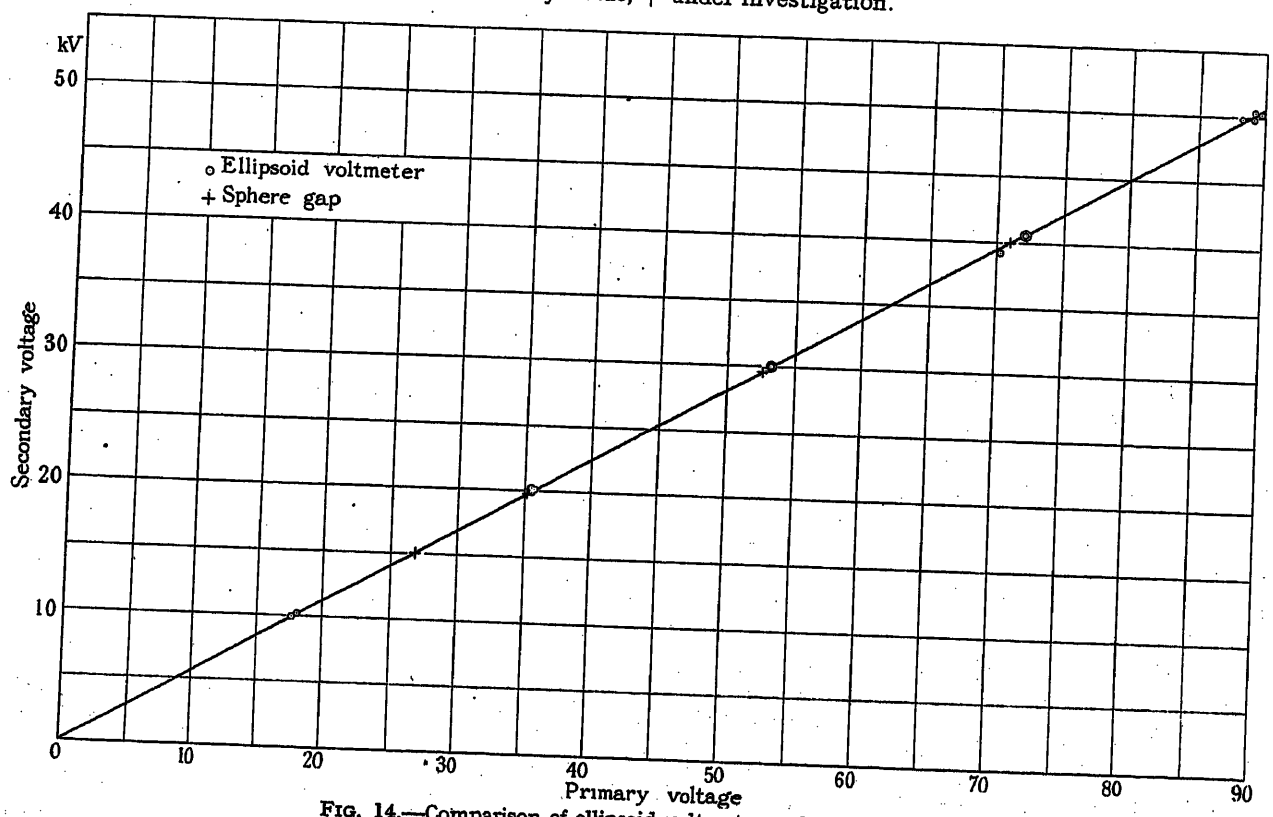


FIG. 14.—Comparison of ellipsoid voltmeter and sphere gap.

Having regard to the above agreement it is considered possible to measure voltages of the order of 100 000 to 200 000 to an accuracy of 1 part in 1 000 by this absolute method. It is, in fact, easier to measure these voltages with high accuracy than those of a lower order, say 1 000 volts, and, unlike the sphere spark-gap method, continuous observations of the voltage can be made by it. The requirements of a standard are fulfilled by the instrument in that it may be readily reproduced from dimensions to any desired order of accuracy and that it is absolute, in electrostatic measure.

ACKNOWLEDGMENT.

The authors wish to take this opportunity of thanking the Department of Scientific and Industrial Research for a grant to one of them which has enabled the work to be carried out.

[The discussion on this paper will be found on page 16.]

DISCUSSION BEFORE THE INSTITUTION, 21ST JANUARY, 1932.

Dr. E. H. Rayner: I do not suppose that a paper on the absolute measurement of voltage has been brought before the Institution in the last 50 years. Possibly the late Lord Kelvin discussed the subject in connection with the attracted-disc electrometer, but I know of no effective work in this country since then. At the Bureau of Standards a few years ago I saw parts of an absolute attracted-disc electrometer for about 200 kV which was being constructed to the designs of Mr. H. B. Brooks. I am not aware what results have been obtained from it. There is also the very beautiful instrument of the attracted-disc type working in compressed nitrogen up to 250 kV (R.M.S.) which was designed by A. Palm.* Under a pressure of 12 atmospheres the clearance can be kept down to 4 cm. The instrument is of an absolute type, the voltage being calculated from the measured force and dimensions. With these exceptions the subject has been left severely alone by workers aiming at some precision, and has only been employed by teachers and examiners as a method of testing the learning or powers of imagination of students. One reason for this is that voltage is a more abstract quantity to deal with than current or resistance. Resistance can be incorporated in a material of suitable character and can be given a wide range of values and forms to suit the particular purpose required. Current can be confined within conductors of desired dimensions and form. Voltage, however, is a more abstruse quantity to deal with, especially from an absolute point of view. Accurate comparisons of voltages are generally easy and simple; but they are usually carried out by means of currents, and thus the problems associated with absolute measurements are avoided. This difficulty is reflected in the recognized methods of dealing with the electromagnetic units—the ohm, ampere, and volt. The ohm and the ampere are regarded as the primary quantities, to be determined on the absolute C.G.S. system, and the volt is derived from them. Without attempting to be dogmatic on the subject I would point out that there may be a philosophical cause underlying the technical choice of the two primary quantities. Resistance has the dimensions of velocity (LT^{-1}), so that it is fundamentally simpler than the other two, which contain the third quantity, mass. To evaluate resistance in absolute measure a dimensional quantity L can be used. Induction is of this type. The other dimensional quantity T^{-1} may be an angular velocity, since an angle is of no dimensions. Resistance may therefore be evaluated as a product of induction and angular velocity. It is obtained in this manner by the Lorenz apparatus, the inductance being calculated from very accurate dimensional measurements of solenoids carrying about 1 ampere. The solenoids are commonly wound in grooves cut in marble cylinders by means of specially accurate lathes. The second quantity, current, has the dimensions $M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$, i.e. the square root of MLT^{-2}, the latter being the dimensions of force. One form of apparatus for evaluating a current in absolute measure is the ampere balance. Solenoids whose linear dimensions are capable of being very accurately measured are wound on marble cylinders for the fixed and for the smaller moving coils, the latter being suspended from the ends of a very sensitive balance. The coils exert an axial force on one another, exactly as in the ordinary Kelvin balance. The force is balanced by the earth's attraction on a mass of a few grammes. The weight of the mass is required, necessitating a knowledge of the local value of "g" to about 5 significant figures. The dimensions of voltage ($M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}$) are more complicated, and this quantity is regarded internationally as being derived from the other two. In actual practice an international ampere is not easily "portable" outside the laboratory in which the apparatus for generating it is situated. It is therefore made portable in terms of a portable resistance of known value and a portable source of constant voltage. This source has to be taken as nature provides it; the essential element is constancy, reproducibility also being very desirable. In practice the Weston cadmium cell is chosen, and its e.m.f. in volts as determined from the ohm and ampere naturally contains fractional digits. The value is 1·018+, depending upon temperature and details of manufacture. A paper on absolute measurements affords an opportunity for noting the past, present, and future position of the electrical units on which much research has been and is being devoted. In 1881 an International Conference held in Paris formulated a common system of electrical units for the whole world founded upon the centimetre, gramme, and second, and independent of the properties of particular substances. It was, however, known that a system of units could not be established at once on such foundations. The art of realizing the units to the accuracy required would take much research and development. We have to thank Clerk Maxwell, Kelvin, and Fleeming Jenkin, in particular, who attended that conference, for the scientific method and foresight which restrained the delegates from adopting the easier empirical units then in common use, e.g. those depending upon the resistance of metals having a particular form. The approach to the establishment of the international units on an absolute basis of sufficient trustworthiness has been long. The goal has not yet been attained, but the end of the journey is in sight. In the meantime empirical units in close agreement with them have been in world-wide use. These have from time to time been brought closer in value to the C.G.S. units, as methods and apparatus have been developed, chiefly in recent years in the principal national laboratories of the world. We must remember, however, that fundamental work of high precision was carried out by pioneer workers in earlier years. Not the least important was that done in this country by Maxwell, Rayleigh, Kelvin, Carey Foster, and Glazebrook. This fundamental work is being actively pursued at the present time. Members of the staffs of three of the national laboratories have met in the past year, and

* A. PALM: *Zeitschrift für Technische Physik*, 1920, vol. 1, p. 137.

have worked together for some weeks on the task of carrying out comparisons of the electrical units as maintained at their national laboratories. It is hoped that before long the subject will be on a sufficiently firm basis to enable the empirical units, depending upon the resistivity of mercury and the electrochemistry of silver salts, to be displaced as methods of realizing a common international system of units. The time which has elapsed since 1881 may seem long, the end being still unattained after 50 years. The reason is that the goal has become more difficult of attainment with each decade. Whereas an accuracy of 1 part in 1 000 would have been very welcome at one time, to-day we must have 1 in 100 000. It has been found necessary to aim at this degree of agreement among primary international electrical standards, in order to ensure that the thousands of high-class working standards throughout the world, in all the various branches of the electrical industry, may have the same numerical value assigned to them to the accuracy within which they are capable of being effectively used. The international units are therefore defined to six significant figures in order to ensure adequate agreement, with the knowledge that they are appreciably different from the C.G.S. units. The difference is not large, the greatest discrepancy being perhaps 20 parts in 100 000; when the change to the C.G.S. units is made (and it is hoped to do this by international agreement before long) the result will be practically inappreciable in all ordinary measurements. The measurement of voltage without making use of an electric current resolves itself into the determination of the value of an electric field. This may be done either by observing the effect of the field on an object immersed in it, or by measuring the mechanical force on a conductor forming a boundary of the field. The authors have chosen the former method, involving a 3-electrode type of instrument; while the attracted-disc electrometer, a 2-electrode type, makes use of the latter. The conditions of the problem, particularly as regards the attraction type of instrument, are as follows. In the disc electrometer the force per cm^2 is

$$\frac{1}{4\pi}(\text{Potential gradient})^2 = \frac{1}{4\pi}\cdot\frac{V^2}{d^2}$$

If $V = 1 = 300$ volts, and $d = 1$ cm, then $F = 1/(4\pi)$ dyne, which is less than 0·0001 g. A practical instrument for higher voltages might have a gradient of 25 C.G.S. units per cm, i.e. 7 500 volts per cm. The force on an area of 100 cm^2 would then be about 5 000 dynes (less than 5 g). This at once gives an idea of the difficulty of the absolute measurement of voltage. To obtain a sufficiently intense force for measurement to a high degree of precision (1 in 10 000 or 1 in 100 000) an intense electric field of the order of 5 000 volts per cm has to be used. If the voltage is considerably less than 5 000 volts much smaller working distances than 1 cm may be necessary, and this distance must be known to 1 part in 20 000 if an accuracy of 1 part in 10 000 is aimed at. Further, the 5 g per 100 cm^2 mentioned above would usually have to be an addition to a larger dead weight. The computation of the effective area of an attracted disc, allowing for its edges, is a serious matter. A standard of voltage of the order of 5 000 volts would be inconvenient. If it were to be of practical use it would be necessary to derive the numerical voltage of a standard cell from it, and in order that it might be regarded as a step in generating a unit for international purposes this step-down would have to be determined with an accuracy of 1 in 100 000. The authors by skill and perseverance have arrived at the results given in Table 9, but in my opinion the foundation of some of the many steps on the journey are not as sound as the results seem to indicate. They depend on various quantities: there is the measurement of the voltmeter in Column 1, which is used as a secondary standard for the measurement of high voltage, the primary standard of which is the electric strength of air (Column 2). I confess to a doubt as to the trustworthiness of the breakdown of air as an accurate standard of voltage for precision purposes. The authors suggest on page 1 that differences of 2 per cent may occur, and that by taking sufficient readings a result reliable to 1 in 1 000 is obtainable. This seems to me a doubtful method of obtaining accuracy, and it depends on the real value of someone else's measurements of similar phenomena, made with different apparatus and in different surroundings. The form factor of the machine and equipment has to be known to a high degree of accuracy; for this purpose an oscillograph has been relied upon as an instrument of high precision, accuracies of values to 4 and 5 significant figures depending upon its indications. The authors finally arrive at a value for the number of volts in an electrostatic unit field, approximately 300 (last column). The apparent accuracy of Column 8—5 or 6 significant figures—is arrived at by multiplying the previous column by 100 (the 100-cm distance between the plates). The last two digits of Column 8 are therefore of no significance. I should much have preferred to have seen the arrangement worked backwards, as follows. Measure experimentally the electric field by oscillations, calculate the voltage from the product of field and separation, assume the value of the number of volts (about 300) in 1 electrostatic unit, and deduce the spark-over voltage, knowing the form factor. The four significant figures in the last column of Table 9 imply a knowledge of the spark-gap setting to the same degree of precision. There is no mention of the method adopted of obtaining this accuracy, nor is the size of the spheres stated. There is a serious limitation as regards the use of the swinging-ellipsoid method. The electric field at the ends of the ellipsoid is many times the average value in the space surrounding it. The authors give an instance of 28 times. This means that a large separation of the inducing plates must be used for comparatively low voltages, in order to prevent the production of corona at the ends of the ellipsoid. They use a field up to 1·7 electrostatic units per cm, i.e. 500 volts per cm (see Table 9, Column 7), whereas other methods involving a parallel-plate condenser have enabled fields of the order of 10 000 volts per cm (i.e. 20 times as much) to be satisfactorily used. The authors talk of measuring up to 200 kilovolts. Their actual measurements seem to have been only carried up to about one-third of this figure, and three times the voltage would require apparatus of about three times the

linear dimensions. For many purposes the measurement of the peak value of the voltage is more important than that of R.M.S. voltage. The peak value is the quantity required in determining electric strength, and its use avoids any assumptions as to form factor of the generating plant or ratio of the transformer. The authors' method would seem to be difficult to apply to peak-value measurements, and the measurement of steady high d.c. voltages of the order of 100 to 200 kV would prove difficult, as the ellipsoid and its supports could not be maintained at nearly such a high voltage as under alternating fields. Leakage would become

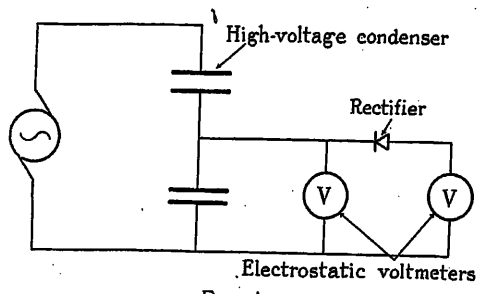


FIG. A.

troublesome. It seems to me that the authors have gone a long and difficult way round when shorter, simpler, and considerably more precise methods of measuring high voltages are available for proving the correctness of their instrument. Measurements of voltage usually entail the use of a potential divider. Up to alternating voltages of 20 or 40 kV, resistor dividers are commonly used. Above 100 kV, capacitance dividers are very valuable. They may take the form of a high-voltage air condenser in series with a fixed or a variable mica condenser, the voltage on the latter being measured by an electrostatic instrument capable of an accuracy of

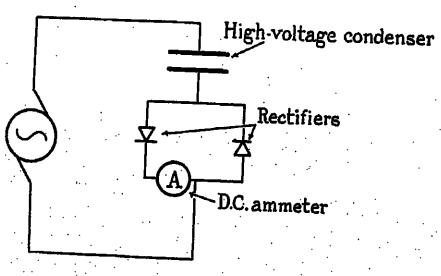


FIG. B.

a few parts in 10 000. An accurate knowledge of the ratio of the capacitances is required, and this can be obtained by an audio-frequency bridge measurement (Fig. A). The method is at once applicable also to peak-value measurements, by rectifying the voltage and using another electrostatic voltmeter. This way of determining the peak value can be compared with the rectified-current method, which does not involve the use of a potential divider but requires an accurate knowledge of the capacitance of the high-voltage condenser (Fig. B). My colleagues at the National Physical Laboratory have compared these methods up to about 1 000 kV, and have found them to give the same value to 1 or 2 parts in 1 000. The results and the details of the methods have been published by the Institution.*

Dr. A. Russell: I had the privilege of sitting in Lord Kelvin's classes some 50 years ago, when he discussed the properties of ellipsoids enthusiastically and at great length. Those, however, were the days before Prof. Thornton's applications of the theory were made. No one would have appreciated this ellipsoidal method more than Kelvin. Fig. 14, showing how the readings of Whitehead and Castellain agree with those obtained by the authors' method, would have given him great satisfaction. Treatises on absolute measurements always give one the impression that the measurements are immensely difficult, as indeed they are if one attempts to obtain the highest accuracy. As regards the value of c, the ratio of the electromagnetic to the electrostatic unit of charge, this was roughly determined 60 or 70 years ago at Glasgow University by one of Kelvin's assistants. Sir F. E. Smith and others have shown that the value of the ratio can be found in a student's laboratory to an accuracy of 1 per cent. I once weighed the attraction between two spheres by means of a chemical balance at voltages between 20 000 and 30 000 volts, and obtained values for c which were less than 1 per cent inaccurate. No special precautions were taken. The balance was made ready for the test in about an hour. Ordinary metal balls, such as are employed in Wimshurst machines, were used, and I was surprised to get such accurate results, seeing that the balls were only approximately spherical. I found out subsequently that Snow Harris, when weighing electrostatic attractions a century ago, had also noticed this effect. I believe Kelvin proved theoretically that the attraction between metal bodies is independent of their exact shape; thus at the same distance two ellipsoids will attract each other with almost the same force as two spheres. Although practically all the experimenters who use metal spheres for absolute measurements take great pains to make them mechanically perfect, judging from some experimental evidence I have examined, much of their labour is unnecessary. I remember once being surprised when I found out mathematically how little the capacitance of an ellipsoid changes when its shape is varied, provided that the volume remains constant.

Dr. C. V. Drysdale: Like Dr. Rayner, I have some difficulty in understanding why the authors consider that the attracted-disc type of absolute voltmeter is unsuitable for high voltages. The electric strength of air at ordinary atmospheric pressure is of the order of 30 000 volts per cm, and therefore with a reasonable factor of safety and allowing for an ordinary form factor, we are fairly safe in working at 6 000 or 7 000 volts per cm. Under such circumstances the force between two parallel discs is of the order of a few grammes for a disc area of 100 cm^2. Such a disc, made of aluminium, need not have a total mass of more than 10 or 12 g, and the measurement of the mass to that degree of accuracy by means of a chemical balance is surely a matter of everyday experience. Furthermore, I cannot see why there should be any difficulty about the use of

* R. DAVIS, G. W. BOWDLER, and W. G. STANDRING: "The Measurement of High Voltages, with Special Reference to the Measurement of Peak Voltages," *Journal I.E.E.*, 1930, vol. 68, p. 1222.

the instrument. In the first place, the high-voltage plate can be above the working plate with the attracted disc in it. The whole of the working parts of the instrument could be at earth potential, and I think it is clear that the dimensions would be less than the authors indicate. Assuming (as I think is justifiable) that we can work with a higher electrostatic stress and that the distribution of the electrostatic field at the surface of the plates is no less uniform than in the intervening space, it would seem that even for voltages of 200 kV the plates need be only 35 to 40 cm apart, and, using the same ratio of dimensions as has been adopted by the authors, plates of about 60 or 65-cm diameter with well-curved edges should be sufficient. Moreover, I think that such an instrument could easily be made. The disc electrometer is more simple for use at very high voltages. It involves no greater stresses, as the high-voltage plate is merely put at such a height that the voltage gradient in the air is kept below the safe limit. If the distance apart of the plates is as large as 35 or 40 cm, it is not so essential that the planes of the plate and of its guard ring should be so absolutely identical as they are in the low-voltage instrument. It is a small matter to support the attracted disc on springs, and by using a little optical lever we could get a deflectional instrument. With a separation of 35 to 40 cm, a 0·1 mm movement of the disc above or below the plane of the plate cannot be a serious factor, and this displacement would be more than sufficient for a large deflection. On the other hand, the condenser-potentiometer method of working lends itself to a very high degree of accuracy, provided that the electrostatic voltmeter is of constant capacitance. If the lower-voltage condenser is of sufficiently high capacitance small variations of the instrument capacitance do not matter. I do not see why a very high order of accuracy should not be obtained by means of this arrangement. Had I been confronted with the problem of producing an absolute voltmeter for high voltages, I should have designed an instrument on the lines of the old guard-ring electrometer, but I fully appreciate the theoretical and experimental skill of the authors in producing the first absolute instrument for such high voltages.

Mr. W. J. John: The authors' results would be more satisfactory if their apparatus had been checked against some more reliable standard than the one they have adopted; the condenser arrangement described by Dr. Rayner would be excellent for checking purposes. There are several points of detail in the paper to which I should like to refer. On page 4 the three possible values given for e^2 are 0·97761, 0·97914, and 0·97872, showing a maximum variation of about 1·5 parts in 1 000. Such a difference is rather disturbing, because the all-important dimensions L and N depend on e. Again, tests were made to establish the uniformity of the field parallel to the plates. Should not other measurements have been made to establish the uniformity of the field in a direction at right angles to the plates? If the instrument is to be used commercially, in place of sphere-gaps, say, it must be fitted with a wind shield, and it seems to me that the Pyrex glass wind-shield and the bayonet joint illustrated in Fig. 4 must prevent uniformity of the field in a direction at right angles to the plates. It is interesting to note the authors' statements that a difference of 2 per cent is possible between individual sphere-gap readings and that it is necessary to take the mean of many readings to obtain results reliable to 1 part in 1 000. The belief is apparently held in many test-rooms that the sphere-gap is accurate to much narrower limits and that only a single reading is necessary. I should like to ask whether the authors can see any objection to the use of their instrument at voltages of the order of 1 000 kV. The problem of accurately measuring voltages of this order is a very difficult one, and I am interested to note from Dr. Rayner's remarks that the condenser method enables one to measure 1 000 kV with accuracy. How many readings of the authors' instrument are necessary to obtain accurate results in any given case? Is it better than the sphere-gap in this respect?

Mr. F. L. Best: The instrument described by the authors gives indications proportional to the R.M.S. voltage, so that if two equal voltages are applied, the first being direct and the second alternating, the instrument will give the same deflection in each case, irrespective of the wave-form of the a.c. voltage. There is some similarity between the measurement of magnetic fields by a small magnetic needle and the measurement of electrostatic fields by an ellipsoid, in that the observation of the periodic time is the only one taken. The authors explain that the ellipsoid is used because it is practically the only body of suitable shape for which the full theory has been developed. The ellipsoid would appear to be the ideal body from another point of view, namely that because of its rounded surfaces it will not so readily give rise to brush discharge and corona when placed in very strong electrostatic fields. There is little doubt that an absolute method of measuring high voltages, particularly alternating high voltages, is necessary. It is remarkable that the "grid" scheme has been evolved and put into operation without such a standard being developed, much less employed. In view of the enormous quantities of power to be transmitted over the grid system at high voltages, it becomes of increasing importance that the exact voltage should be known, for the power delivered to a circuit is proportional to the square of the voltage, and a small percentage inaccuracy in the high-tension voltage may lead to a considerable loss of power. With regard to Prof. Thornton's statement that the instrument is suitable for use on direct current, it is well known that one cannot employ the condenser multiplier for the measurement of high-tension direct current. If one attempts to do so, the reading of the indicating instrument (assumed to be itself an electrostatic voltmeter) will either creep up and beyond its full scale limit, or else down until it reads zero. The explanation is simple. It is not possible to get two condensers whose leakances are in the ratio of their capacitances. Thus over a period of time one condenser is charged up more than the other. I should like to ask, therefore, what happens in the case of the ellipsoid voltmeter on direct current, regarding it as two condensers in series. Also, what is the effect of impressing a static charge on the ellipsoid? The theory of the instrument (page 2) involves the moment of inertia of the ellipsoid, and I

should be interested to know how it is possible to determine this quantity accurately Presumably it would be the subject of a secondary experiment, comparison being made with an accurately turned cylinder. Whether this or another absolute standard comes into use, it will be interesting to see which of the present-day industrial methods of measuring high voltages will survive in the future. The most popular method in use at the moment, of course, is that of the potential transformer. In conclusion, I should like to associate myself with Dr. Rayner and express regret that the authors' results have been compared with those obtained by means of a sphere-gap. In spite of the difficulties of determining the constants of the ellipsoid, and the considerable amount of mathematical work which lies behind the simple observations made, the ellipsoid voltmeter can be rendered more reliable and accurate than the sphere-gap.

Mr. S. Whitehead: The most salient feature of the authors' method is that it avoids the actual measurement of a force by transforming it into the observation of a time of oscillation. The measurement of small forces is usually rather difficult, and in dealing with gravitational forces, for example, it is much easier to make measurements with a pendulum than with a torsion balance. In view of what has been said as to the advantages of the attracted-disc electrometer at high voltages, it is significant that at the present time there are available three types of attracted-disc instruments, but that none of these is both precise and absolute. First, there is the Abraham voltmeter or Kelvin volt-balance, which does not aim at precision, and in most forms of which the movement of the attracted disc is sufficient to prevent high accuracy. Secondly, there is the type in which the moving plate is very much reduced in size and is allowed to rotate rather than to move, its slight motion being amplified optically. Thirdly, there is the type in which the moving plate is replaced by a fibre, the motion of which can be observed through a microscope. The last two have been devised comparatively recently, and their object is to reduce the size of the moving or attracted plate, but neither is absolute. I should like to ask the authors whether they have determined the constants of the voltmeter by both the oscillation and the direct deflection methods, and whether they have deduced from these measurements the linear dimensions upon which the constants depend. It would be of interest to compare the constants of the instrument used (*a*) as an oscillator and (*b*) with direct deflections. If k is the constant under the first condition and k_1 is the constant under the second, i.e. in the notation of Section (10) k_1 is $\sqrt{(A/D)}$, then it may be shown that if k and k_1 are taken under the same conditions, $k_1^2 = k^2 n_0^2 D^2$. The quantity n_0 can be found if desired from the moment of inertia and torsion constant, while D is the spacing if k is the "field" constant given in the paper. If k is the "voltage" constant, $k_1^2 = k^2 n_0^2$. As regards the use of the sphere-gap for high-voltage measurement, the results given in the paper confirm those which Mr. Castellain and I obtained when making calibrations of the 62·5-mm sphere-gap. In our paper* we stated that we did not regard the sphere-gap as comparable with a precision voltmeter; nevertheless, my experience in the course of those and other experiments shows that under suitable conditions the sphere-gap will give consistent values for a week—or possibly weeks—at a time. It will not, however, give consistent results for months at a time. The greatest difficulty in connection with the use of the sphere-gap is to know when it will go wrong. I agree with Dr. Rayner in advising the use of a condenser potential-divider, which in the Electrical Research Association is employed for the routine measurement of higher voltages. The potential divider is inexpensive and easy to make, and its ratio can be obtained to a fair order of accuracy by calibration. If a suitable design is adopted one can be sure that the ratio will remain constant, so that if there is an error it will be a consistent error throughout the measurements. The potential divider can be adapted for use as an absolute null method; by means of an electrometer one can balance the given alternating potential against a continuous potential from a d.c. potentiometer which is standardized in the normal manner. Although I have actually used this method,* I am not prepared to recommend it, because the difficulties of the electrometer are such that a high degree of precision can be attained but not maintained. With regard to Prof. Thornton's question as to the value for the velocity of light which was inherent in the measurements made by Mr. Castellain and myself, our measurements were in international volts and therefore the normal value for the velocity of light will be modified by the difference between international volts and true C.G.S. units. I should like to ask whether the authors have examined the effect of extraneous objects upon the field between the plates. What are the screening conditions which must be insisted upon? It seems to me that a considerable clear space will be necessary in order to obtain the highest accuracy, in view of the fact that the electric field used for the purpose of measurement is small. The problem of ionization in the air is a possible serious difficulty in the present instrument. Have the authors made any experiments with irradiation by ultra-violet light to determine the effect of artificially-introduced ions? By using an enclosure with a suitable window it is possible to remove the initial ionization of the chamber, and then to reintroduce ionization in a fairly well-controlled manner by means of radiation.

Prof. W. M. Thornton and **Dr. W. G. Thompson** (*in reply*):—Dr. Rayner has given an excellent review of the whole question of absolute units and of the peculiar position of the volt as in theory one of the two fundamental units but in practice, and by the ruling of the International Electrotechnical Commission, derived from the units of current and resistance. In the present investigation we were concerned in the first instance with finding an accurate voltmeter by which sphere spark-gaps and the ionic wind voltmeter could be calibrated or compared, and after considering the Bureau of Standards attracted-disc electrometer—as exemplifying the latest developments in the theory and design of that type of instrument—we came to the conclusion that the

* *Journal I.E.E.*, 1931, vol. 69, p. 898.

* S. Whitehead and D. Barham: *Journal of Scientific Instruments*, 1930, vol. 7, p. 337.

ellipsoid voltmeter had advantages as a standard which the other had not. Our experience has confirmed this. The ellipsoid voltmeter is simple to make, robust, easily read, and gives true R.M.S. values. There was no intention of using the instrument to measure c except as a check on the order of accuracy of the results, and the values obtained (see Table 9) are an example of how the check was applied. That the values of the significant figures of c are as good as they are gave us the assurance we desired, and we now use the instrument frequently when comparing R.M.S. and crest values of our 250-kV transformer supplied by different machines and on different loads, the crest values being measured by means of the sphere spark-gap. In reply to Dr. Rayner's question as to range, this particular instrument with the 100-cm spacing has had a peak voltage of 500 kV across it without flashing over. In the work described in the paper it was only used up to 60 kV, for at that time we had only one transformer available from which a sine-wave secondary voltage could be obtained. For peak values we now use the ionic wind voltmeter calibrated by the sphere-gap. For use in test rooms this instrument is very convenient as it avoids all spark-discharge measurements. Its use for this purpose will be described in a subsequent paper. One purpose of our work was simplification of accurate measurement of test-room voltages, where each kind of apparatus under test distorts the wave-form to a different extent and gives different peak values.

Dr. Russell's remarks on the accuracy possible in electrostatic measurements are very interesting. In the case of attracted spheres, or indeed in any case in which the force is a simple pull or push, the precise form of the surfaces may not be essential to accuracy; but where the induced charge on a surface varies with its movement in the field the form of the surface is more important. For this reason, and as a result of our experience with the earlier ellipsoids, we had ours accurately shaped by Messrs. Hilger.

We agree with Dr. Drysdale that the attracted-plate voltmeter is at first sight simpler and has the advantage that higher fields may be used, but the corrections to be applied are much more difficult to determine and are very complex, as was shown by Chester Snow.* It is possible to make the present instrument read both as an attracted-disc voltmeter and as an ellipsoid instrument, and further—by measuring the current from the disc—to determine c directly by this instrument alone. We have not gone into the question of the accuracy of condenser potentiometers on bad voltage wave-forms, but I should have thought that the influence of harmonics, which are always difficult to avoid in test-room practice, would have had a serious effect on the tapped readings compared with the line voltage.

In reply to Mr. John, we were fully aware of the need for careful determinations of the eccentricity, and the value of c finally obtained is a justification for the value chosen. We estimate that the mean value of e^2 chosen is correct to 1 part in 1 000, but $(1 - e^2)$, which is the determining factor in the calculation of L and N, has a mean departure of 0·5 per cent. The final values are probably correct to 1 part in 1 000. The gradient between the plates was undoubtedly uniform. It is only when there is a conduction current between electrodes that the voltage gradient between them is affected, and in our case—with alternating fields and air at atmospheric pressure—the amplitudes of any ionic movements are too small to affect the field shape. In test-room practice measurements of high voltages are made by means of the sphere spark-gap, the condenser-current method, the potential divider, and the ratio of transformation—and the derived values rarely coincide. In the present case the ellipsoid voltmeter gives readings close to the ratio of transformation values. With regard to the measurement of voltages of the order of 1 000 kV, we can say definitely that if R.M.S. readings are desired the ellipsoid voltmeter will give them, but for peak values the null-reading ionic wind instrument is the best known to us.

Mr. Best raises the important question of why the "grid" has been put into commission without a standard high voltage being specified or required. The answer, we think, is that if there had then been such a standard it would have been used to specify voltage limits. As yet the demand for a high-voltage standard does not appear to have been felt. A great deal of work was done on the standard chemical cell for use with the d.c. potentiometer, and perhaps the time is approaching when it will be recognized that it is as easy to construct a high-voltage standard as it is to make a standard cell. The use of the ellipsoid voltmeter on direct current is made possible by the fact that there is no conduction current to the ellipsoid, and it therefore does not acquire charge; on the other hand, if the ellipsoid were charged it would not affect the readings in an alternating field, for there is no resultant torque. If the ellipsoid were to be charged it would have to be by a proof-plane, since the suspension is non-conducting. We are glad to have Mr. Best's opinion that the ellipsoid voltmeter can be made more reliable and accurate than the sphere-gap, but it is possible that an improved form of the latter may shortly be available.

Mr. Whitehead makes the interesting comment that the instrument transforms the measurement of a feeble force into that of a time. This is an important point which may account for the consistency of the readings. It is a new thing in voltage measurement to obtain the readings by timing swings. This mode of working is comparable perhaps with the measurement of speed in the Lorenz method of standardizing resistance, and it makes for high accuracy. The instrument, like all air condensers, must not be placed too near other sources of high voltage, though in most test rooms it is not usual to have more than one source of high potential or other metallic parts at high potential close together in one place. Ionization does not appear to have any effect; illumination by an arc lamp has none. There is no form of electrical discharge to be observed at working pressures on either the ellipsoid or the plates. In this respect the design is satisfactory. The conversion of the value obtained for c at the end of Table 9, so as to give both sphere-gap voltages and those observed by the ellipsoid voltmeter in C.G.S. units, is obtained by multiplying the figure $2{\cdot}995 \times 10^{10}$ by 1·00049, the ratio of the international to the C.G.S. volt. This gives $2{\cdot}996 \times 10^{10}$ as the corrected value.

* *Bureau of Standards Journal of Research*, 1928, vol. 1, p. 513.

Mr. J. A. Harle: The paper describes an attempt to reduce extra-high-voltage measurements to an absolute basis, so that electrical quantities may be measured in terms of non-electrical dimensions. The two forms of the authors' instrument—the oscillating and the static-deflection ellipsoid voltmeters—each have their own particular applications. The former would be particularly suitable for metering on high-voltage systems, where it would form the absolute standard for the voltage-measuring device. The deflection type of instrument would appear to be useful in research work and for standardizing other classes of measuring instruments used for routine testing purposes, but it would be subject to the drawback that it is difficult to obtain pure sine waves on large-power high-voltage test equipments at an economical cost. In consequence of the wave-form distortion on generating plant and the effect of the magnetizing currents of the testing transformer and the capacitance of the transformer windings and load, peak-voltage readings appear to be essential at present with most high-power voltage testing equipments. With regard to the deflection-type instrument, I should be glad if the authors could state the maximum voltage response in kV per sec. at which the device would follow the applied voltage, and, in addition, the maximum rate at which the mirror would follow the ellipsoid. These two factors would appear to constitute a possible source of trouble in connection with the use of the instrument for testing purposes, as rates of rise of from 5 to 10 kV per sec. are in use. As regards Fig. 7, is the extra load due to the voltmeter taken as the arithmetical or the vectorial difference between the currents? The latter would more truly represent the load effect. Have the authors considered placing their instrument in a high-pressure enclosure on similar lines to that of the Hartmann and Braun precision voltmeter? While this arrangement would give high field strengths without corona for a given space occupied, it is possible that the effect of the ellipsoid on the field would be appreciably greater and would result in a more distorted scale. The authors' view on the possibilities of applying this suggestion to the design of a voltmeter for higher voltages than those mentioned in the paper, in order to reduce the space occupied by the instrument, would be interesting. Have any difficulties been encountered due to interference set up by adjacent bodies?

Mr. E. Fawssett: The theory of the authors' absolute standard voltmeter involves the assumption that the insertion of the ellipsoid in the field does not alter its distribution: if this assumption were false the instrument would break one of the first rules of measurement—that the apparatus employed must not of itself alter the quantity to be determined. I am not altogether convinced that the extremely high absolute accuracy claimed by the authors for such a difficult measurement is entirely justified on this score. As regards Section (5), dealing with the calibration by means of a sphere spark-gap, in my opinion it is a case of good fortune rather than a proof of high accuracy that the calibrations agree so well with those of Whitehead and Castellain, as I am not yet convinced that the mean values of spark-gap determinations are necessarily correct to a high order of accuracy, and the wave-form correction factor is, relatively speaking, large and erratic. The relation between R.M.S. and spark-gap reading on such a wave as (*d*), Fig. 6A, would surely be appreciably affected by the difference in steepness of the two sides of the wave, according to which represents rising voltage, for the same R.M.S. value. These detail criticisms are, however, only prompted by a slight doubt as to whether absolute accuracy can be guaranteed to so close a limit as 1 in 1 000.

Mr. T. R. Warren: The results obtained by the authors show that a new and much improved method of determining the value of high potentials in absolute measure will shortly be available. There are, however, one or two points in the paper which call for criticism. In my opinion the value of e should be chosen smaller, in order to prevent any small discrepancies due to imperfect workmanship giving rise to relatively large errors when determining the values of L and N. Although it will be conceded that any appreciable departure from a value nearly equal to unity will give rise to a reduction in torque for given values of F and V, I gather that there is already more than sufficient torque available to enable the required degree of accuracy to be obtained. I do not agree with the statement (page 4) that the torque on the ellipsoid is proportional to the product of the charge on any ring element of the surface and its distance from the axis of suspension, since the expression for the torque arrived at in this way, using the formula for the distribution of charge given on page 7, does not coincide with the expression given on page 2. It is important to determine the extent of field distortion due to the reaction on the plates when the ellipsoid is placed in position, since the spacing of the plates for a given degree of accuracy is largely dependent upon this factor. The theory given in Section (6), however, contains several inaccuracies, and I would suggest to the authors that they should proceed as follows. Consider an image of the ellipsoid in each plate. The field at the ellipsoid due to corresponding ring charges on each image is given by

$$\partial X_1 = \frac{4\pi X b^2 x \partial x}{Na^2(D-x)^2}$$

Therefore
$$X_1 = \frac{4\pi X b^2}{Na^2}\int_{-a}^{+a}\frac{x dx}{(D-x)^2}$$
$$= \frac{4\pi X b^2}{Na^2}\left(\frac{2aD}{D^2-a^2} - \log_e\frac{D+a}{D-a}\right)$$

Hence
$$\frac{X_1}{X} = \frac{8\pi a b^2(2D^2+a^2)}{3ND^3(D^2-a^2)}$$ (neglecting terms containing the fifth and higher powers of a)
$$= \frac{16\pi a b^2}{3ND^3}$$ (since a^2 is small as compared with D^2)

By taking successive images, the above expression becomes

$$\frac{X_1}{X} = \frac{16\pi ab^2}{3ND^3}\left(1 - \frac{1}{2^3} + \frac{1}{3^3} - \frac{1}{4^3} + \ldots\right)$$

The percentage increases in the field for the various spacings shown in Table 4 are now found to be as given in the following table.

D	Percentage increase of field
cm	
25	0·04215
50	0·005269
75	0·001561
100	0·000659

These values are much less than those given by the authors, and they indicate that a closer spacing of the plates is permissible without fear of introducing any appreciable error due to reaction.

Prof. W. M. Thornton and **Dr. W. G. Thompson** (*in reply*): In reply to Mr. Harle, the instrument should be regarded rather as a standard than as suitable for routine testing. Peak-voltage readings are much more easily obtained by the ionic wind voltmeter, using a null method. The response to change of voltage is slow, and the ellipsoid instrument is not suitable for observation of rapid changes. The voltages in Fig. 7 were added vectorially. With regard to enclosure, this would be difficult if the instrument had to be used for absolute measurements, but it might be made about half the size and without the metal-frame support. This is the final form it will probably take.

Mr. Fawssett's suggestion that the field distribution may be so greatly changed by the presence of the ellipsoid that the charges on the pole plates are modified, is considered in Section (6) of the paper. The field in the immediate neighbourhood of the ellipsoid must necessarily converge on it in order to give the condition that a field only enters or leaves a metallic surface at right angles to it. A good deal of time and care was spent in determining the influence of wave distortion such as that shown in Fig. 6A: the result is Fig 6B. It would have unduly increased the length of the paper to have given details of the analysis of the wave-forms. If the oscillograph is in perfect condition and the records are taken with a revolving-film camera these wave-forms are as accurate representations of voltage waves as it is possible to obtain. The records agree very closely. They were much enlarged, and then analysed laboriously by the method of ordinates. Fig. 6B gives the ratios by which the peak values calculated by multiplying the observed R.M.S. values by $\sqrt{2}$, were multiplied to give true peak values of the wave-forms. They could then be compared with sphere-gap measurements of peak voltages.

Mr. Warren is right in thinking that the difficulties involved in making an elongated ellipsoid to an exact profile are greater than when it is less pointed, but the eccentricity chosen (0·989) is that which gives $LN/(L - N)$ a maximum value. The expression on page 2 for the torque is calculated from that on a ring element in the manner stated. The distance between such an element and its image should surely be $(D - 2x)$, and there are several images to consider in the same manner; but it is satisfactory to see that his method gives still smaller values than ours for the reaction at the pole plates. With conducting ellipsoids 2·5 cm long having the same proportions it is possible to bring the spacing down to 20 cm, provided that the field is kept low. We hope that this instrument may commend itself to "grid" engineers and others as a simple standard of reference for high voltages; but the paper should be regarded as a preliminary study of a new and absolute method of measuring high voltages rather than as the description of a finished instrument. The work is being repeated and comparisons are being made between this and all other available methods.

REPORT OF THE COUNCIL FOR THE YEAR 1931–1932, PRESENTED AT THE ANNUAL GENERAL MEETING OF 5TH MAY, 1932.

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REPORT.

The Council, at the Sixtieth Annual General Meeting of The Institution of Electrical Engineers, present to the members their Report for the year 1931–32, covering approximately the period from the 1st April, 1931, to the 31st March, 1932.

The Council desire once more to thank most cordially the many members, too numerous to be mentioned by name, who, by placing their services at the disposal of the Institution, serving on its committees, etc., contribute so materially to the fulfilment of its objects.

(1) MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since the 1st April, 1931, are shown in a table included in Appendix A.

The following table shows the net growth of membership for the last 10 years:—

Year	Membership	Increase
1923	10 911	+ 636
1924	11 415	+ 504
1925	11 743	+ 328
1926	12 142	+ 399
1927	12 647	+ 505
1928	13 043	+ 396
1929	13 561	+ 518
1930	14 200	+ 639
1931	14 670	+ 470
1932	14 884	+ 214

(2) EXAMINATIONS.

Graduateship Examinations were held in May and November, 1931, in London, Belfast, Birmingham, Cardiff, Dublin, Glasgow, Manchester, Newcastle-on-Tyne, Norwich, and Southampton, and, in November only, in Australia, Brazil, Ceylon, F.M.S., Hong Kong, India, New Zealand, and South Africa.

During the year a number of candidates were permitted to fulfil the educational requirements for Associate Membership by the submission of satisfactory written papers or theses in lieu of an Examination.

Mr. J. R. Shewan was awarded the Page Prize (value £5) for the best Thesis submitted, his subject being "The Theoretical and Practical Training of the Apprentice Electrician."

(3) NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING.

England and Wales.—In 1931 the Joint Standing Committee, representing the Board of Education and

the Institution, was associated with the final examinations of 150 courses at colleges and schools in England and Wales approved in connection with the above certificates and diplomas.

The final examinations were held during the summer of 1931 and the number of awards was as follows:—

592 Ordinary Certificates.
279 Higher Certificates (including 8 Post-Higher Certificates).
8 Ordinary Diplomas.
3 Higher Diplomas.

Scotland.—In conjunction with the Scottish Education Department, the Institution was associated with 5 courses in Scotland during the year under review.

The final examinations were held during the summer and the number of awards was as follows:—

5 Ordinary Certificates.
3 Higher Certificates.
11 Higher Diplomas.

(4) Honorary Member.

The Council have pleasure in recording that, as announced at the Ordinary Meeting on the 21st January, 1932, they have elected Mr. William Morris Mordey, Past-President, to be an Honorary Member of the Institution.

(5) Faraday Medal.

The eleventh award of the Faraday Medal was made by the Council to Sir Oliver Lodge, D.Sc., F.R.S., Honorary Member.

(6) Minister of Transport.

The Council are especially gratified at the appointment of Mr. Percy John Pybus, Member, to the office of Minister of Transport and offer him the Institution's hearty congratulations.

(7) Honours and Distinctions Conferred on Members.

O.M.

Bragg, Sir William Henry, K.B.E., M.A., D.Sc., F.R.S. (Honorary Member).

Knighthood.

Goodman, William George T. (Member).

O.B.E.

Cohen, Bertram Sydney (Member).
Withycombe, Robert (Associate Member).

The Council are also pleased to place on record the Election of the Secretary of the Institution as an Honorary Member of the Société Française des Électriciens.

(8) Deaths.

The Council regret to have to record the death of the following 85 members of the Institution during the year:—

Honorary Member.

Edison, T. A.

Members.

Aldridge T. H. U.
Allan, P. F.
Bailey, F.
Baron, J. T.
Black, A. S.
Bulkley, J. N.
Clinker, R. C.
Dando, H. A.
Denham, J.
Drake, B.
Esskildsen, M. K.
Fuller, G.
Gregory, J. P.
Griffith, W. G., B.Sc.(Eng.).
Gwyther, C. W.
Hancock, W. J., D.Sc.
Harrison, Gen. Sir R., G.C.B., C.M.G.
Julius, C. H.
Leaf, H. M., D.S.O.
Moffett, F. J., B.A.
Nalder, F. H.
Packham, W. B.
Prentice, H. N.
Shaw, James H.
Smith, H. B.
Soldan, C. P.
Taylor, H. M.
Teasdel, J. E.
Walker, S. F.
Walton, A. H.
Wilkinson, H. D.
Wilson, Prof. E.
Wilson, S. N.
Winning, W. L.
Wright, Arthur

Associate Members.

Austin, E. P.
Belfield, S. St. G. C.
Brownell, J.
Burke, R. T.
Cooper, W. James
Cuthbert, M.
Darker, A. H.
Davies, F. H.
Ellis, W.
Foggo, J. J.
Gilbert, H. W.
Giles, F. C.
Grut, C. A.
Haley, W. E.
Harrison, T. C.
Haydon, G. S.
Hunter, K. H. W., B.Sc
Johnston, J. S.
Lakey, E. A.
Lambourn, W. C.
Law, G. C.
Lines, S. L. B.
Lund, A.
Maybury, Major P. T., B.Sc.Tech.
Miles, J. W.
Parkhurst, F. C.
Robertson, T. E., O.B.E.
Tate, T. F.
Tetley, T. R. H.
Thompson, F. W.
Wray, W. J. Roberts.

Companion.

Renwick, Sir H. B., Bart., K.B.E.

Associates.

Barnes, S. E.
Brash, J.
Chisholm, A. H.
Darlington, W. E.
Goold, R. L.
McGuigan, W.
Whitehouse, A. E.

Graduates.

Kershaw, R.
Kruger, N. D., B.Sc.
Lapraik, D. R., B.Sc.
Williams, H. L.

Students.

Calver, R. F. J.
Chapman, K. G.
Chapple, J.
Maidwell, C. L.
Shuttleworth, J. H.
Sleight, L.

(9) Institution Building.

The Institution continues to grant facilities for the free use of its premises to kindred societies in connection with their meetings, and 200 such meetings were held during the past year.

Arising out of the scheme for floodlighting public buildings in September, 1931, on the occasion of the

International Illumination Congress and the Faraday Centenary Celebrations, the Council, who gave wholehearted support to the scheme, decided that the Institution Building should be floodlighted not only for the period concerned, but at other times, and a permanent equipment has accordingly been installed. At present the Building is lighted until 8.30 p.m. every day (excluding Sundays) during the winter months.

The Institution's largest tenant, the British Broadcasting Corporation, will be vacating at an early date the premises which it has occupied in the Institution building since 1923. Some of the space so released is being let to the British Electrical Development Association and the Electric Lamp Manufacturers' Association who are extending their offices, and steps are being taken to obtain suitable tenants for the remainder of the available space, the rentals for which are lower than those prevailing in the Strand district.

(10) Oil Paintings.

During the past year the painting of the late Dr. de Ferranti, referred to in the last Annual Report, has been hung in the Lecture Theatre. The portrait, which is the work of Mr. David Jagger, was presented by Mr. H. Marryat.

Reproductions of all the portraits in the Lecture Theatre have been issued with recent numbers of the *Journal*.

(11) Unauthorized Use of Membership Initials.

During the past year there have been several cases of the use, by unauthorized persons, of initials or descriptions implying that they were members of the Institution, and, with one exception, it has been possible to ensure the discontinuance of the practice by the persons concerned without the necessity of taking legal action.

Legal action became necessary, however, as the result of the renewed use of the initials "A.M.I.E.E." by an ex-Student, against whom a perpetual injunction had been obtained in 1928. A report of this case has already been published in the *Journal* (April, 1932, No. 424, p. 473).

(12) Meetings.

During the past twelve months, 467 meetings have been held in London and the Local Centres by the members, the Council, and the various Committees. A detailed statement is given in Appendix B.

(13) Premiums.

The Premiums awarded by the Council for papers read at meetings or accepted for the *Journal* will be announced at the Annual General Meeting.*

(14) Coopers Hill War Memorial Prize.

The award of the Coopers Hill War Memorial Prize, which consists of a Bronze Medal, a parchment Certificate, and a Money Prize of £29, fell this year to the Institution, and the Council selected for the award Mr. M. G. Say, Ph.D., M.Sc., for his paper on "High Voltage Underground Cables." Five papers were submitted for consideration. Only Corporate Members of the Institution under 35 years of age are eligible to compete.

* See page 148.

The Prize consists of two awards, one of which is made annually by the Institution of Civil Engineers, and the other triennially in turn by the Institution of Electrical Engineers, the School of Military Engineering, Chatham, and the School of Forestry, Oxford.

(15) Local Centres and Sub-Centres.

Reports from the Committees of the Centres and Sub-Centres indicate that the attendances at the meetings and the interest in the discussions, etc., have been well sustained.

The President attended functions and meetings at the Centres at Birmingham, Cardiff, Dublin, Glasgow, Leeds, Liverpool, Manchester, and Newcastle-on-Tyne, as well as at the Hampshire, Sheffield, and Tees-Side Sub-Centres.

On each occasion the President addressed the members and was gratified at the activities of these branches of the Institution and impressed by their great value in extending its influence and prestige.

Full details of the meetings and other activities of the Local Centres and Sub-Centres are contained in the Annual Reports presented each year to the local members.

Members are reminded that local technical libraries have been established by the Institution at Birmingham, Dublin, Leeds, Loughborough, Manchester, Middlesbrough, and Newcastle.

Full particulars of the arrangements for borrowing or referring to the books at these libraries can be obtained on application to the Local Honorary Secretaries.

(16) Local Honorary Secretaries Abroad.

During the Session, the Council received the resignations of Mr. A. Gibbs (Local Honorary Secretary for New Zealand) and of Mr. A. C. Kelly (Argentine), and wish to tender the Institution's cordial thanks to these members for their zealous work on behalf of the Institution during their tenure of office. In their places, the Council have appointed Mr. A. C. Owen and Mr. R. G. Parrott respectively.

The Council also appointed Professor P. H. Fraenkel as Local Honorary Secretary for Western Australia in place of the late Dr. W. J. Hancock.

(17) Activities of Overseas Members.

In addition to the Local Committees, which, as stated in the last Annual Report, have already been set up in New South Wales, Victoria and Tasmania, South Australia, Western Australia, New Zealand, and the Transvaal, a Local Committee has now been set up in Queensland and Committees are also in process of formation in the following towns in India—Bombay, Calcutta, Lahore, and Madras.

Social gatherings, and in some cases meetings for the reading and discussion of papers, have been held with success in New South Wales, Queensland, and Victoria, and Faraday Centenary Celebration meetings have been held jointly with other scientific bodies in New South Wales, Queensland, and New Zealand.

The question of increasing further the overseas activities of the Institution is being carefully considered by the Overseas Activities Committee set up by the Council.

(18) Wireless Section.

The interest and activities of the Wireless Section continue to be well maintained. Nine meetings have been held, at which eight papers were read and two discussions took place, one on technical problems in connection with "Television" and the other on "Selectivity." In addition, five papers have been published or accepted for publication in the *Journal*. The average attendance at the meetings was 129, as compared with 107 for last Session.

The Council approved the issue of a list of members of the Section, and copies were posted with the March number of the *Wireless Proceedings*. The number of members is 590.

(19) Meter and Instrument Section.

Eight meetings of the Meter and Instrument Section have been held during the past year, the average attendance being 80, which compares with 79 for the preceding 12 months. The meetings have been uniformly successful and the discussions have been well sustained and interesting. The programme included an Informal Debate to which there were no fewer than 58 contributors.

A most successful Summer Visit to Cambridge took place on the 2nd May, 1931. The party, which numbered over 150 members and ladies, enjoyed the hospitality of the directors of the Cambridge Instrument Co., Ltd., whose works were inspected and who provided lunch for the visitors, and of Prof. C. E. Inglis, O.B.E., M.A., LL.D., F.R.S., who threw open the Engineering Laboratory for inspection and provided tea. Some of the Colleges were also visited. The success of this visit, as well as of the Section Dinner which was held on the 11th December, 1931, was most gratifying.

The Rules have been revised so as to provide for the immediate Past-Chairman to serve on the Committee. There are now 556 members in the Section, and a list of names is about to be published.

(20) Informal Meetings.

Ten meetings have been held during the Session, the average attendance being 62, as against 55 last year.

The Informal Meetings Committee again cordially invite members to write to the Secretary indicating subjects which they wish to suggest for discussion. Offers from members to open discussions will also be welcomed and carefully considered by the Committee.

(21) Students' Sections.

The eight Students' Sections, viz. at London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, and Sheffield, have carried out during the Session a very full programme of meetings, visits to works, and social functions. Full details and accounts have been given from time to time in the *Students' Quarterly Journal*.

The actual membership of the eight Students' Sections is in the aggregate 3 300, which includes some 1 200 Graduates under the age of 28, who are now entitled under the Bye-laws to the same privileges as Students.

The "Students' Lectures" were delivered this Session by Dr. C. C. Garrard and Mr. R. E. G. Horley, at the places indicated:—

Lecturer	*Subject*	*Place*
Dr. C. C. Garrard	"Switchgear"	Leeds
		Newcastle-on-Tyne
		Sheffield
		Glasgow } Scottish
		Edinburgh } Section
Mr. R. E. G. Horley	"Oil-filled Cables"	London
		Birmingham
		Liverpool
		Manchester

The total attendances at the nine Lectures, which were greatly appreciated, were approximately 700, compared with 530 for the nine Lectures given last Session by other lecturers. Although this increase is gratifying, it is hoped that the Lectures will receive even greater support next Session, as it is felt that the attendances should be still higher, taking into account the total membership of the Sections.

Eight papers were submitted by Students, and by Graduates under the age of 28, in the competition for the second Students' Prize of £10 offered for the best paper on the subject of "The Relations between Economics and Engineering." After due consideration it was decided that a Prize, value £5, be awarded on this occasion to Mr. C. M. Johnston (Graduate) for the paper submitted by him, and that a further Prize of £5 be offered this Session for the best paper received on the same subject. The award of this Prize will be announced as soon as possible.

In order to afford an opportunity for the personal interchange of views on matters of common interest to the various Sections, arrangements have been made for an Annual Meeting of the Honorary Secretaries of the Sections to be held in London, and the first of these meetings took place on the 5th February, when a very useful and interesting discussion took place on points of organization and routine.

The Students' Section Summer Tour was held in Northern Italy and Switzerland from 25th July until 4th August, 61 Students and Graduates taking part.

The party travelled from London to Milan, where they remained for five days. During that time visits were made to Messrs. Pirelli Ltd., Messrs. Brown Boveri, Milan University, and the Engineering School, the trunk telephone exchange, and a number of hydro-electric power stations belonging to the Cisalpino Electricity Supply Co.

From Milan the party proceeded to Glion (above Montreux) for the remainder of the tour. From here visits were made to the Barbarine Dam, hydro-electric power stations at Château Naye, Sembrancher, and Orsières, and a large preserving factory at Martigny.

Both in Milan and Montreux, time was devoted to seeing local scenery and visiting places of general interest.

The Council desire to express the thanks of the Institution for the hospitable welcome extended by those who entertained the party and gave facilities for visits to works, etc. The meeting was highly successful and thanks are due to Mr. T. H. Lockett, the then Honorary Assistant Secretary of the London Students'

Section, for his very capable handling of the organization of the tour on behalf of the Committee of the Section.

(22) "Students' Quarterly Journal."

The *Students' Quarterly Journal* has continued to make excellent progress. The support received in the shape of articles and suggestions has been so great, and the standard so high, that it has not been necessary to go outside the Students' Section for any of the material, and there is every indication that this desirable state of affairs will be maintained.

The influence of the publication in stimulating attendances at meetings and improving the corporate spirit of the individual members has been evidenced in several directions, while a very happy co-operation is growing up between the various Sections in different parts of the country. The publication is also greatly appreciated by overseas readers who find it an invaluable link with their old associations.

(23) Summer Meeting.

In anticipation that many members would be attracted to London in September, 1931, by the Faraday Centenary Celebrations, the International Illumination Congress, and the Annual Conversazione, it was considered opportune to hold the Summer Meeting in London during that month, and an extensive programme of visits and other functions took place from Tuesday the 22nd to Friday the 25th September. The Council were glad to be able to welcome on the occasion of this Meeting a party of members of the Société Française des Électriciens and their ladies.

The Meeting commenced on Tuesday morning with a Conference at Kingsway Hall, an account of which has already been given in the *Journal*, and ended with a Ball at Grosvenor House on Friday evening. The 23rd September was set aside for a Private View and the Official Opening of the Faraday Exhibition, and the remaining time was spent in visits to works and other places of interest, including Hampton Court, Windsor Castle, and some of the Colleges at Oxford. The thanks of the Council have been sent to the following firms and bodies whose hospitality was cordially appreciated by all the members and ladies, some 420, who took part:—

British Broadcasting Corporation (Brookman's Park transmitting station).
Messrs. Callender's Cable and Construction Co., Ltd. (Erith works).
Messrs. Carreras Limited.
Central Electricity Board (132-kV transforming station at Swanscombe).
County of London Electric Supply Co., Ltd. (Barking generating station).
Messrs. Fraser and Chalmers, Ltd.
General Electric Co., Ltd. [Osram G.E.C. lamp works and M.O. valve works at Hammersmith; Osram G.E.C. glass works and lamp works (No. 7 Factory), and the research laboratories at Wembley].
Gramophone Co., Ltd.
Messrs. W. T. Henley's Telegraph Works Co., Ltd. (Gravesend works).
Messrs. Huntley and Palmers, Ltd.
London General Omnibus Co., Ltd. (Chiswick overhaul and repair works).
London Power Co., Ltd. (Deptford power station).
Messrs. J. Lyons and Co., Ltd. (Greenford chocolate factory).
Messrs. Morris Motors, Ltd. (Cowley works).
National Physical Laboratory.
North Metropolitan Electric Power Supply Co. (Brimsdown generating station.)
Port of London Authority (King George V Dock, etc.).
Post Office [Post Office (London) Railway and Baldock radio station].
Royal Zoological Society (Electrical installation at the Reptile House, Zoological Gardens).
Messrs. Standard Telephones and Cables, Ltd. (Hendon works).
Underground Railway Co. (Carriage overhaul works, Acton).

(24) Faraday Lecture.

The Faraday Lecture this Session was delivered by Prof. J. K. Catterson-Smith, M.Eng., who chose as his subject "Everyday Uses of Electricity." The Lecture was given at Dublin, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, and Swansea. Prof. Catterson-Smith will also give the Lecture at Aberdeen before the Session closes.

The six Lectures so far delivered this Session have been attended by a total audience of approximately 3 230, of whom over 2 570 were non-members.

(25) Reviews of Progress.

Continuing the series of reviews of progress in electrical engineering published in the *Journal* since 1926, reviews on the following subjects have been published during 1932:—

Power Stations and Their Equipment.
Radio-Telegraphy and Radio-Telephony.
Telegraphy and Telephony.

The reviews to be published in 1933 will be on the following subjects:—

Electric Traction.
Electrical Equipment of Automobiles.
Electrical Plant and Machinery.
Electricity Applied to Ships.
Electro-Physics.
Industrial, Agricultural, and Domestic Applications, including Illumination and Tariffs.

(26) Scholarships.

The following Scholarships have been awarded by the Council during the Session:—

Ferranti Scholarship.

(Annual Value £250; tenable for two years.)

W. G. Thompson, Ph.D. (Armstrong College, Newcastle-on-Tyne).

Duddell Scholarship.

(Annual Value £150; tenable for three years.)

C. H. W. Clark (Sevenoaks Grammar School).

Silvanus Thompson Scholarship.

(Annual Value £100, plus tuition fees; tenable for two years.)

C. H. Lackey (Messrs. A. Reyrolle and Co. Ltd.).

David Hughes Scholarship.

(Value £100; tenable for one year.)

G. L. d'Ombrain [City and Guilds (Engineering) College].

Salomons Scholarship.

(Value £100; tenable for one year.)

S. H. Padel (Manchester College of Technology).

Paul Scholarship.

(Annual Value £50; tenable for two years.)

W. T. Darwin (London County Council School of Engineering and Navigation).

Thorrowgood Scholarship.

(Annual Value £25; tenable for two years.)

P. W. Ottley (The Underground Electric Railway Co. of London, Ltd.).

War Thanksgiving Education and Research Fund (No. 1).

The Council have made grants from the above Fund for research purposes as follows:—

£50 each to:—F. J. Clark (East London College).
J. H. Wagstaff (University College, London).

£25 to:—Miss W. Hackett (Birmingham University).

With the exception of the Paul Scholarship, which is awarded in alternate years only, all the above scholarships and grants are awarded annually.

(27) Faraday Centenary Celebrations.

The Faraday Centenary Celebrations which took place in September, 1931, were an unqualified success. A full account will be found in the November, 1931, issue (No. 419) of the *Journal*. The report of the Organizing Committee of the Exhibition was published in the January, 1932, issue (No. 421, p. 164).

(28) Hughes Centenary.

The centenary of the birth of David Edward Hughes, who was born on the 16th May, 1831, was commemorated by the Institution on the 14th May, 1931, when a discourse on the life and work of Hughes was given by Mr. Sydney Evershed. The discourse was printed in the *Journal* in October, 1931 (No. 418, p. 1245).

(29) Varley Centenary.

The centenary of the births of Cromwell Fleetwood Varley (6th April, 1828) and Samuel Alfred Varley (22nd March, 1832) will be commemorated by the Institution on the 5th May, when a discourse on their lives and work will be delivered by Lieut.-Col. A. G. Lee, O.B.E., M.C., B.Sc.

(30) Swan Memorial Fund.

It was stated in the last Annual Report that an appeal had been published in January, 1931, with the support of the Institution and the Royal Photographic Society of Great Britain, for funds for the establishment of a memorial to Sir Joseph Swan, the inventor, *inter alia*, of the incandescent electric lamp, in the form of scholarships in electrical engineering science to be administered by the Institution. The final result has been that a sum of approximately £3 000 has been received which, it is regretted, is considerably short of the desired total of £5 000. It will therefore only be possible to establish one scholarship, instead of two as originally proposed. The Conditions of Award for this scholarship are at present being drawn up and the first award will probably be made in 1932.

(31) International Relations.

Paris International Electrical Congress, 1932.

The object of this Congress is the celebration of the 50th anniversary of the first International Electricity Congress which took place in Paris in 1881, when fundamental and far-reaching decisions regarding electrical units were arrived at.

The Council have set up a British Organizing Committee to collaborate with the French authorities in arranging for the presentation of papers by British authors for this Congress, which will be held in Paris in July, 1932. Ten papers by British authors have been sent through the British Committee to Paris for this purpose.

International Union of Suppliers and Distributors of Electrical Energy.

The Council have considered the question of becoming formally associated with this Union and have recommended that the electricity supply organizations in this country should join it as Adherent Members.

(32) Anniversary Celebrations and Conferences.

During the year under review, the Institution has been represented at Anniversary Celebrations and Conferences, etc., arranged by other bodies as shown in the following table:—

Name of Body	*Nature and Date of Function*	*Name of I.E.E. Representative*
Association of Teachers in Technical Institutions	Annual Conference, Manchester (23–26 May, 1931)	Prof. Miles Walker, D.Sc.
British Association for the Advancement of Science	Centenary Celebrations (23–30 Sept., 1931)	Mr. Clifford C. Paterson, O.B.E. (then President).
Cambridge University	Clerk Maxwell Centenary Celebrations (1 & 2 Oct., 1931)	Mr. Clifford C. Paterson, O.B.E. (Past President).
Carnegie Institute of Technology	Third International Conference on Bituminous Coal, Pittsburg (16–21 Nov., 1931)	Mr. Gano Dunn (Local Hon. Secretary for the U.S.A.).
International Commission on Illumination	International Illumination Congress (1–19 Sept., 1931)	Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (Past President). Mr. P. Good. Mr. H. T. Harrison. Prof. J. T. MacGregor-Morris. Dr. J. W. T. Walsh.

Name of Body	*Nature and Date of Function*	*Name of I.E.E. Representative*
Royal Dublin Society	Bi-Centenary Celebrations (22–26 June, 1931)	Mr. F. H. Whysall (Chairman, Irish Centre).
Royal Institution	Faraday Centenary Celebrations (19–25 Sept., 1931)	Mr. Clifford C. Paterson, O.B.E. (then President).
Royal Sanitary Institute	Annual Congress, Glasgow (4–11 July, 1931)	Mr. E. Seddon (Chairman, Scottish Centre).
Société Française des Électriciens	Faraday Centenary Celebrations, Paris (26 Nov., 1931)	Mr. J. M. Donaldson, M.C. (President).
		Mr. Clifford C. Paterson, O.B.E. (Past President).
		Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (Past President).
		Mr. P. F. Rowell (Secretary).

(33) Local Wireless Sections in Canada.

The scheme for the formation of Local Wireless Sections in Canada, in co-operation with the Engineering Institute of Canada, is almost complete and it is hoped that it will be possible shortly to inform members in Canada of the details of the scheme.

(34) Annual Conversazione.

The Faraday Exhibition at the Royal Albert Hall afforded an opportunity for the Annual Conversazione to be held there on the 22nd September, 1931, and it was made the occasion of a Private View of the Exhibition which was opened to the public on the following day. The guests included, among others, many delegates to the Faraday Centenary Celebrations, and the total attendance of members and guests was 2 400.

(35) Annual Dinner.

The Annual Dinner was held at the Connaught Rooms, London, on the 4th February, 1932, when nearly 700 members and guests were present.

An account has been published in the *Journal* (No. 424, p. 470, April, 1932).

(36) Electrical Appointments Board.

The Board keeps a classified register of members seeking positions, and the Secretary of the Board will gladly put employers in touch with highly qualified electrical engineers.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the register.

(37) Library.

During the year, 189 books and pamphlets were presented to the Reference Library by members and others, and 137 volumes were purchased. The total number of readers for the year was 6 762, of whom 560 were non-members, as against 4 359 and 336 respectively in 1930–31.

Sixty-eight new volumes were added to the Lending Library and 2 522 books were issued to 1 007 borrowers, the corresponding numbers for the previous year being 2 444 and 938 respectively.

(38) Gifts to the Institution.

The Council express their cordial thanks to the donors of the following gifts to the Institution:—

Donor	*Gift*
Elektrotechnischer Verein of Berlin	A replica of the original Gauss-Weber electromagnetic telegraph made in 1833.
Mr. A. Evelyn Barnard ..	A small plaster bust of Michael Faraday by M. Noble, 1854.
	An engraved reproduction of A. Blaikley's painting of Faraday lecturing at the Royal Institution.
Mr. F. A. Downs	An early milliamperemeter.
Mr. J. Forrester	A voltaic pile made by the late F. V. Andersen.
	An early amperemeter.
Sir Robert Hadfield, D.Sc., F.R.S.	A plaque of Faraday.

(39) "Science Abstracts."

The Physics volume of *Science Abstracts* for 1931 contains 4 365 abstracts, as compared with 4 165 in 1930. The Electrical Engineering volume contains 2 607 abstracts, as compared with 2 537.

The very slight interest taken in *Science Abstracts* by the general body of members is still a matter of considerable disappointment to the Council. The publication, which appears monthly in two sections, namely, Section "A" (Physics) and Section "B" (Electrical Engineering), consists of full abstracts from the leading scientific and technical journals and the proceedings of learned societies of the whole world, and presents in a form convenient for immediate reference a complete and concise record of the progress of physical science and electrical engineering. It is therefore surprising that, out of a membership of some 14 900, fewer than 1 400 subscribe to *Science Abstracts*, only 805 members subscribing to both Sections and 579 to Section "B."

The Council regret to record that this represents a decrease of 100 in the total number of subscribers during the last twelve months, and they earnestly hope that greater support will be given to the publication in the future. *Science Abstracts* may be obtained, if ordered in advance, by Students of the Institution, as well as by Graduates under the age of 28, at the special rate of 7s. 6d. per annum for both Sections, or 5s. for either the Physics or the Electrical Engineering Section, and by all other members of the Institution at 20s. for both Sections, or 12s. 6d. for either Section alone, the rates charged to the general public being £1 15s. per Section, or £3 for both Sections.

(40) Model General Conditions for Contracts.

The proposed set of Model Conditions "E" for the supply, laying, and erection of cables at home is still under consideration. The Committee set up by the Council to deal with the matter has been increased to include representatives of additional interested Associations.

(41) London Building Act, 1930.

The Institution was given an opportunity to suggest amendments to the above, and the following representations were made:—

(*a*) Electricity generating stations, except in regard to architectural appearance, should be fully exempted from the Act;

(*b*) Electricity substations should be similarly exempted, except those which abut on other buildings; and

(*c*) The right of appeal to the Tribunal provided for in the Act should be allowed to electricity authorities.

(42) Regulations for the Electrical Equipment of Buildings.

The Wiring Regulations Committee are proceeding with the revision of the present (Ninth) Edition of the Regulations and, in order to expedite the work, have appointed a small Executive Committee to complete the revision and to deal with the numerous matters which arise from time to time in connection with the Regulations. The Wiring Regulations Committee collaborate not only with the British Standards Institution in this country, but also with the organizations in Australia and New Zealand which deal with regulations for electrical installations.

An Advisory Sub-Committee assists in matters relating to the application of the Regulations, and answers inquiries as to interpretation in particular cases. Several new sub-committees have been set up to consider special Sections of the Regulations, particularly from the point of view of recent developments such as luminous tube signs, electric clocks, etc. In order to provide for such switchgear as "splitter units," a new clause (69 M) relating to distribution boards was issued in May, 1931, in the form of a Supplement to the Ninth Edition.

There is a steadily increasing demand for copies of the Regulations (the Ninth Edition is now in its 21st thousand), a sure indication of the growing appreciation of the Regulations and of the extent to which they are being adopted.

(43) Electricity Regulations.

On the 19th June, 1931, the Electricity Commissioners published three Supplementary Regulations for Securing the Safety of the Public, under the Electricity (Supply) Acts, 1882 to 1928. These relate to "Insulation or Protection," "Underground Shafts, etc." and "Service Lines into Consumers' Premises." It is understood that the remainder of the Safety and Supply Regulations will be published within the next few months.

(44) Radiological and Electro-Medical Technical Committee.

The above Committee has been set up by the Council to obtain papers on radiological and electro-medical subjects, and to deal with such other matters as may be referred to it by the Council, the aim being to stimulate interest in the electrical engineering aspect of radiology. The Committee is representative of electrical engineers, medical men, and radiographers.

(45) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1931, the total assets of the Fund amounted to £20 461 11s. 9d., of which £17 811 17s. 2d. was on Capital Account, and £2 649 14s. 7d. in respect of unexpended Income. The donations and subscriptions to the Fund in 1931 amounted to £3 069 0s. 8d., in which amount are included the proceeds of Golf Competitions organized by the Mersey and North Wales (Liverpool) and Scottish Centres. A legacy of £100 was also received from the executors of the late Mr. E. Garcke.

In the course of 1931, grants were made to 38 persons, amounting to a total of £1 870 7s. 6d. During the last few years, the annual totals of the grants made have shown a distinct increase from year to year.

The Council most earnestly desire to bring the Fund to the notice of all members of the Institution. Donations and promises of annual subscriptions of any amount will be gratefully received.

(46) Summary of Annual Accounts.

Income and Expenditure.—After making provision for contingencies, there is a deficit on the Revenue Account for the year ended 31st December, 1931, of £427 13s. 7d. This deficit, which has been carried to the debit of the General Fund, and compares with a balance to the good of £3 616 2s. 2d. in 1930, is entirely accounted for by items of non-recurring expenditure (Faraday Centenary Exhibition, etc.) specially indicated in the Revenue Account.

Assets.—Taking the investments at cost and the Institution Building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to	201 998	0	10
against Liabilities	19 597	18	2
leaving a surplus of	182 400	2	8
which, in comparison with that of the year 1930, viz.	182 760	2	3
shows a reduction of	£359	19	7

The surplus of £182 400 2s. 8d. referred to above is made up as follows:—

	£ s. d.	£	s.	d.
Assets.				
Institution building and lease		73 028	6	10
Investments, cash, etc. ..		120 797	12	7
Stock of paper, libraries, and furniture		8 172	1	5
		£201 998	0	10
Less *Liabilities.*				
Trust Fund Accounts ..	346 1 6			
Sundry creditors ..	6 270 15 9			
Overdraft at Bank ..	8 644 4 1			
Repairs Suspense Account	4 035 13 10			
Subscriptions received in advance	301 3 0			
		19 597	18	2
		£182 400	2	8

Investments.—The investments made during the year were as follows:—

	£	s.	d.
£2 400 Ayr County Council 5 per cent "A" Stock (1947–57)	2 484	4	0
£2 400 Union of South Africa 5 per cent Stock (1950–70)	2 436	4	0
	£4 920	8	0

(47) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

Appendix C shows in diagrammatic form the organization of the Institution and the bodies on which it is represented.

APPENDIX A.

MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since April 1, 1931, are shown in the following table:—

	Hon. Mem.	Mem.	Assoc. Mem.	Com.	Assoc.	Grad.	Stud.	TOTAL.
Totals at 1 April, 1931	13	1 973	5 660	115	1 612	2 175	3 122	14 670
Additions during the year:—								
Elected ..	1	3	111	7	72	204	589	987
Reinstated	—	9	5	—	3	2	3	22
Transferred to ..	—	46	234	—	4	360	—	644
Totals..	1	58	350	7	79	566	592	1 653
Deductions during the year:—								
Deceased ..	1	35	31	1	7	4	6	85
Resigned ..	—	22	67	4	46	43	88	270
Lapsed ..	—	5	44	1	63	33	294	440
Transferred from ..	—	—	46	—	33	163	402	644
Totals..	1	62	188	6	149	243	790	1 439
Net Increase								214
Totals at 1 April, 1932	13	1 969	5 822	116	1 542	2 498	2 924	14 884

APPENDIX B.

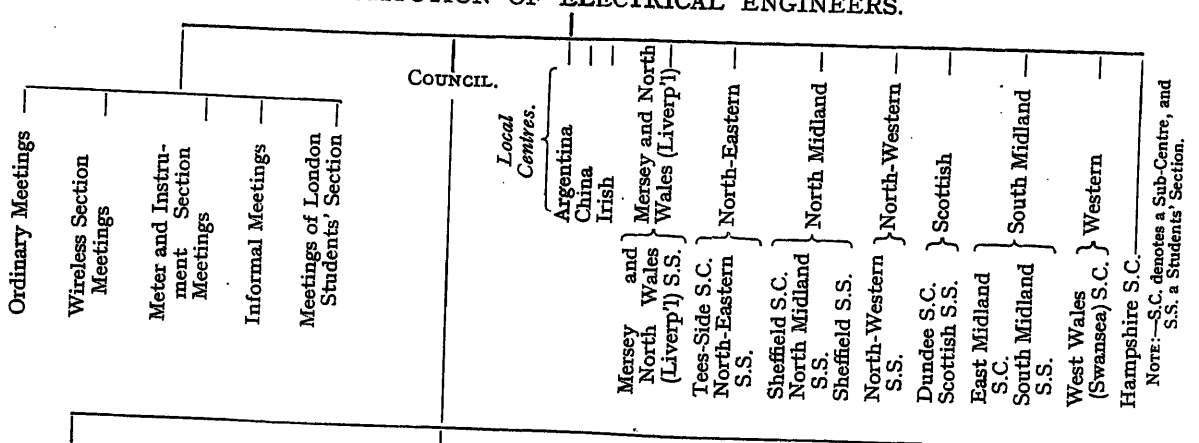
MEETINGS.

The following is a list of the meetings held during the past 12 months:—

Ordinary Meetings ..	18
Annual General Meeting	1
Annual General Meeting (Benevolent Fund)	1
Wireless Section ..	9
Meter and Instrument Section	8
Informal Meetings ..	10
Council Meetings ..	14
Local Centres:—	
Irish	7
Mersey and North Wales (Liverpool)	10
North-Eastern ..	12
North Midland ..	13
North-Western ..	12
Scottish	13
South Midland ..	10
Western	9
Local Sub-Centres:—	
Dundee	7
East Midland ..	9
Hampshire ..	10
Sheffield	7
Tees-Side	8
West Wales (Swansea)	5
Students' Sections:—	
Liverpool	11
London	17
North-Eastern ..	11
North Midland ..	8
North-Western ..	9
Scottish	13
Sheffield	7
South Midland ..	10
Committees:—	
Benevolent Fund ..	5
Examinations ..	6
Faraday Celebrations (and Sub-Committees) ..	5
Finance	13
General Purposes (and Sub-Committee)	8
Informal Meetings	5
International Relations (and Sub-Committee) ..	2
Local Centres ..	2
Membership ..	7
Meter and Instrument Section (and Sub-Committees)	18
National Certificates (England)	4
National Certificates (Scotland)	2
Overseas Activities	6
Papers (and Sub-Committee) ..	10
Scholarships ..	3
"Science Abstracts" (and "Physics" Panel)	4
Wireless Section (and Sub-Committees)	17
Wiring Regulations (and Sub-Committees)	38
Other Committees	33
Total ..	467

APPENDIX C.

THE INSTITUTION OF ELECTRICAL ENGINEERS.



Committees of Council.

- Examinations
- Finance
- General Purposes
- Library and Museum
- Membership
- Papers

Special Committees.

- Benevolent Fund
- E.H.T. Conference, Paris, British National Committee
- Electricity (Supply) Regulations
- Faraday Medal and Honorary Membership Advisory
- Informal Meetings
- International Relations
- Local Centres
- Meter and Instrument Section
- Model General Conditions
- Overseas Activities
- Patent Law
- Scholarships
- "Science Abstracts"
- Ship Electrical Equipment Regulations
- Wireless Section
- Wiring Regulations

Technical Committees.

- Electrical Plant and Machinery, including Marine Applications
- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Industrial, Agricultural and Domestic Applications, including Illumination and Tariffs
- Power Stations and their Equipment
- Radiological and Electro-Medical
- Telegraphs and Telephones
- Traction
- Transmission and Distribution

Overseas Advisory Committees.

- India
- New South Wales
- Queensland
- South Australia
- Victoria and Tasmania
- Western Australia
- New Zealand
- Transvaal

Bodies on which the Institution is Represented.

- Alloys of Iron Research Committee (Royal Society)
- Bristol University
- British Cast Iron Research Association
- British Electrical and Allied Industries Research Association
- British Electrical Development Association
- British National Committee of the International Electrotechnical Commission
- British National Committee, World Power Conference
- British National Illumination Committee of the International Illumination Commission
- British Standards Institution
- City and Guilds of London Institute
- Council for the Preservation of Rural England
- Electrical Association for Women
- Engineering Joint Council
- Imperial College of Science and Technology, Governing Body
- Imperial Minerals Resources Conference, Copper Committee
- Institute of Metals, Corrosion Research Committee
- Institution of Civil Engineers, Engine and Boiler Testing Committee
- International Association for Testing Materials
- International Electrotechnical Commission
- Leeds Municipal Technical Library Committee
- Loughborough Technical College Advisory Committee
- Metalliferous Mining (Cornwall) School, Governing Body
- Middlesbrough Technical College, Governing Body
- National Certificates and Diplomas in Electrical Engineering, Joint Committees for
- National Committee on Physics (Royal Society)
- National Committee on Radio-Telegraphy (Royal Society)
- National Physical Laboratory, General Board
- National Register of Electrical Installation Contractors
- Professional Classes Aid Council
- Radio Manufacturers' Association, Committee on Battery Eliminators
- Royal Engineer Board
- Science Museum, S. Kensington, Advisory Council
- Smoke Abatement League of Great Britain
- Technical and Economic Advisory Council for the Building Industry
- Union of Lancashire and Cheshire Institutes, Panel for Engineering
- War Office Mechanical Warfare Board
- Women's Engineering Society

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1931.

Dr. EXPENDITURE. **Cr.** INCOME.

Year ended 31 Dec., 1930.* £ s. d.	EXPENDITURE	£ s. d.	£ s. d.
	To MANAGEMENT:—		
	Salaries and Wages	13,049 12 2	
	Staff Provident Scheme	1,555 7 2	
	National Insurance	70 17 5	
	Audit Fee	73 10 0	
	Printing	506 1 5	
	Stationery and Office Requisites	604 17 5	
	Addressing Machine Requisites	37 5 7	
	Postage of Correspondence and Notices	845 1 11	
	Telephone	95 1 2	
16,794 9 4	Travelling Expenses	410 1 7	
			17,247 15 10
	„ INSTITUTION BUILDING:—		
	Ground Rent	2,201 0 0	
	Rates	2,854 14 1	
	Heating	293 14 7	
	Lighting and Power	447 14 5	
	Insurance	182 19 6	
	Transferred to Repairs Suspense Account	1,000 0 0	
	†Floodlighting Installation	1,243 11 0	
	Household Requisites and Cleaning	384 15 8	
		8,608 9 3	
4,306 17 9	*Less* Rents from Tenants	5,665 0 0	
452 7 2	„ FURNITURE AND FITTINGS (Repairs and Renewals)		2,943 9 3
	„ JOURNAL:—		394 7 9
	Printing	7,740 12 2	
	Postage	2,633 4 10	
	Wrappers and Envelopes	355 9 2	
		10,729 6 2	
6,224 7 8	*Less* Sales and Advertisements	4,527 18 2	
			6,201 8 0
42 0 9	„ PROCEEDINGS OF THE WIRELESS SECTION (Printing, Postage, etc.: *less* Sales)		10 8
297 15 8	„ STUDENTS' QUARTERLY JOURNAL (Printing, Postage, etc.: *less* Sales)		684 8 7
154 12 2	„ LENDING LIBRARY (Books, Printing, Postage, etc.)		129 0 5
	„ SCIENCE ABSTRACTS:—		
	Abstracting, Editing, Printing, Postage, etc.	5,844 8 3	
155 0 2	*Less* Subscriptions, Sales and Advertisements	5,460 14 6	
			383 13 9
	Carried Forward		£27,984 14 3

Year ended 31 Dec., 1930.* £ s. d.	INCOME	£ s. d.	£ s. d.
37,709 1 9	By SUBSCRIPTIONS		38,611 19 0
995 2 2	„ ENTRANCE FEES AND VELLUM DIPLOMA FEES		982 10 0
130 4 6	„ LIFE COMPOSITIONS		163 2 3
4,682 14 9	„ DIVIDENDS AND INTEREST		5,580 12 2
169 17 8	„ SALES OF "MODEL GENERAL CONDITIONS"		123 18 6
71 16 8	„ SALES OF "WIRING REGULATIONS"		56 2 10
12 5 8	„ SALES OF "SHIP WIRING REGULATIONS"		9 1 7
	„ EXAMINATIONS:—		
	Graduateship Examination (Candidates' Fees and Sale of Papers, *less* Examiners' Fees, Printing, etc.)	232 19 10	
	National Certificates and Diplomas (Candidates' and School Authorities' Fees, *less* Assessors' Fees, Stationery, Postage, Travelling Expenses, etc.)	539 5 5	
597 10 4			772 5 3
	Carried Forward		£46,299 11 7

Dr. EXPENDITURE—*continued.* REVENUE ACCOUNT—*continued.*

INCOME—*continued.*

1930				£ s. d.	£ s. d.
			Brought Forward	..	27,984 14 3
			To INSTITUTION MEETINGS:—		
			Advance Proofs	249 10 3	
			Reporting	144 17 0	
			Grant to London Students' Section ..	61 1 8	
			Honorarium to Kelvin Lecturer ..	25 0 0	
			Refreshments, Assistance, etc. ..	325 12 6	
			Travelling Expenses of Authors of Papers	80 6 0	
			Faraday Lectures	373 19 1	
			Students' Lectures	171 15 2	
1,335	*2*	*11*	Overseas Meetings	50 8 10	
					1,482 10 6
			„ LOCAL CENTRES:—		
			Money Grants (including Travelling Expenses of Authors of Papers) ..	3,229 14 0	
			Travelling Expenses	857 13 7	
4,007	*15*	*7*	Sub-Centre Libraries	88 15 6	
					4,176 3 1
			„ †FARADAY CENTENARY EXHIBITION AND LOCAL CELEBRATIONS		7,802 16 6
240	*19*	*4*	„ PREMIUMS FOR PAPERS		255 5 2
100	*0*	*0*	„ SCHOLARSHIPS		575 7 2
			„ SPECIAL GRANTS:—		
			British Standards Institution ..	1,000 0 0	
			Electrical Research Association ..	1,000 0 0	
			National Illumination Committee ..	32 0 0	
			International Illumination Congress, 1931 (Final instalment and delegates' expenses)	497 7 10	
			Paris Conference on Extra High Tension Systems (Delegates' expenses)	61 3 9	
2,809	*3*	*5*	Technical and Economic Advisory Council for the Building Industry	25 0 0	
					2,615 11 7
			„ †MEMORIAL PLAQUE OF SIR JOSEPH SWAN		165 0 0
			„ †DONATION TOWARDS AMPÈRE MEMORIAL MUSEUM ..		100 0 0
71	*2*	*5*	„ ANNUAL DINNER		73 14 6
589	*15*	*3*	„ CONVERSAZIONE		571 8 11
354	*16*	*1*	„ LEGAL EXPENSES		47 6 0
150	*8*	*5*	„ MISCELLANEOUS EXPENSES		113 12 8
38,112	*11*	*7*			45,963 10 4
			„ AMOUNTS TRANSFERRED TO:—		
277	*12*	*2*	SINKING FUND (Premiums for Redemption of Cost of Building and Lease)	277 12 2	
			GENERAL FUND:—		
130	*4*	*6*	Life Compositions	163 2 3	
286	*18*	*8*	Expenditure on Books and Binding for Library	323 0 5	
7,310	*17*	*6*	(*Surplus for 1930*)		763 14 10
45,423	*9*	*1*			£46,727 5 2

Cr.

1930				£ s. d.
			Brought Forward	46,299 11 7
45,423	*9*	*1*	By DEFICIT CARRIED TO GENERAL FUND	427 13 7
				£46,727 5 2

* These columns do not add up to the totals of Income and Expenditure shown, as some of the items in the Accounts for 1930 did not occur in 1931.
† Non-recurring items of expenditure, amounting to £9,311 7s. 6d.

BALANCE SHEET, 31st DECEMBER, 1931.

Dr. LIABILITIES. | ASSETS. **Cr.**

LIABILITIES	£ s. d.	£ s. d.
To Kelvin Lecture Fund:—		
As per last Balance Sheet		648 13 0
,, Uninvested Balances of Trust Funds		346 1 6
,, Overdraft from Bank		8,644 4 1
,, Sundry Creditors		6,270 15 9
,, Subscriptions received in advance		301 3 0
,, Repairs Suspense Account:—		
Balance at 1st January, 1931	3,670 9 7	
Amount set aside in 1931	1,000 0 0	
	4,670 9 7	
Less Expenditure on Repairs in 1931	634 15 9	
		4,035 13 10
,, Reserve Fund:—		
As per last Balance Sheet		24,940 16 6
Carried Forward		45,187 7 8

ASSETS	£ s. d.	£ s. d.
By Institution Building and Lease:—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	7,772 18 10	
		65,255 8 0
,, Sinking Fund (Surrender Values of Policies for Redemption of Cost of Building and Lease)		7,772 18 10
,, Kelvin Lecture Fund Investment (at cost):— £694 16s. 9d. 5 % War Stock (1929–47)		648 13 0
,, Library (exclusive of the Ronalds Library and Faraday Papers, which are held in trust):—		
As per last Balance Sheet	1,578 9 9	
Additions in 1931	323 0 5	
	1,901 10 2	
Less Depreciation (10 %)	190 3 0	
		1,711 7 2
,, Thompson Memorial Library (Contribution towards purchase)		1,000 0 0
,, Furniture, Fittings, and Apparatus:—		
As per last Balance Sheet	4,565 12 9	
Less Depreciation (5 %)	228 5 8	
		4,337 7 1
,, Sundry Debtors		3,731 10 4
,, Insurance Premiums and Sundry Payments in Advance		752 18 0
,, Stock of Paper, Etc., for Publications		1,123 7 2
,, General and Reserve Funds Investments (at cost):—		
£2,600 Natal Zululand Railways 3 % Debenture Stock	2,270 12 0	
£1,500 London, Midland and Scottish Railway 4 % Preference Stock	1,513 10 4	
£2,000 Assam Bengal Railways 3 % Stock (1931 or after)	1,548 0 6	
£750 Western Australia 4 % Stock (1942–62)	730 8 3	
£750 Union of South Africa 4 % Stock (1943–63)	742 12 0	
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock (1938)	738 15 6	
Carried Forward	7,543 18 7	86,333 9 7

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.* **Cr.** ASSETS—*continued.*

	£ s. d.	£ s. d.
Brought Forward		45,187 7 8
To General Fund:—		
Balance at 1st January, 1931	157,170 12 9	
Life Compositions received in 1931	163 2 3	
Expenditure in 1931 on—		
Books and Binding for Library	323 0 5	
	157,656 15 5	
Less Deficit from Revenue Account for 1931	427 13 7	
	157,229 1 10	
Less Depreciation:—		
Library (*per contra*) £190 3 0		
Furniture, Fittings, and Apparatus (*per contra*) 228 5 8		
	418 8 8	
		156,810 13 2
		£201,998 0 10

	£ s. d.	£ s. d.
Brought Forward		86,333 9 7
By General and Reserve Funds Investments (at cost)—*contd.*		
Brought forward		
£35 East Indian Railway "B" Annuity (1953)	7,543 18 7	
£1,500 South Australia 4 % Stock (1940–60)	791 5 4	
£3,750 5 % War Stock (1929–47)	1,494 10 6	
£19,375 4 % Funding Loan (1960–90)	3,666 4 5	
£8,700 3½ % Conversion Stock (1961 or after)	15,500 0 0	
£11,970 11s. 4 % Consolidated Stock	6,651 3 3	
£1,000 London, Midland and Scottish Railway 5 % Preference Stock (1955)	10,291 6 6	
£5,000 North Metropolitan Power Station 5 % Guaranteed Debenture Stock (1957)	1,020 4 6	
£2,000 London, Midland and Scottish Railway 5 % Redeemable Debenture Stock (1952)	4,988 11 0	
£2,300 East Indian Railway 4½ % Irredeemable Debenture Stock	1,982 5 9	
£5,000 Commonwealth of Australia 5 % Stock (1945–75)	2,019 13 0	
£2,000 Tynemouth Corporation 5 % Stock (1947–57)	4,964 17 6	
£2,500 Stoke-on-Trent Corporation 5 % Stock (1948–68)	2,025 4 0	
£3,500 East Indian Railway 3½ % Debenture Stock (1937)	2,550 6 0	
£5,000 Brighton Corporation 4½ % Stock (1945–75)	2,475 15 6	
£2,000 New South Wales 5¼ % Stock (1947–57)	5,050 8 0	
£2,600 Kenya Government 4½ % Stock (1950)	2,013 19 0	
£3,000 Southern Railway 4 % Debenture Stock	2,483 4 0	
£2,500 India 4½ % Stock (1958–68)	2,520 5 0	
£2,500 Corporation of London 4½ % Debenture Stock (1940–85)	2,329 17 9	
£3,000 Birmingham Corporation 4½ % Stock (1948–68)	2,462 14 0	
£3,000 London County 4½ % Stock (1945–85)	2,906 11 0	
£1,000 Bootle Corporation 4½ % Stock (1949–59)	2,936 11 0	
£10,000 5 % Conversion Stock (1944–64)	967 12 0	
£2,000 Southampton Corporation 5 % Stock (1947–67)	9,888 5 10	
£3,000 Metropolitan Railway 3½ % "A" Debenture Stock	2,027 14 0	
£2,000 Agricultural Mortgage Corporation 5 % Debenture Stock (1959–89)	2,110 5 0	
£2,400 Ayr County Council 5 % "A" Stock (1947–57)	2,080 11 0	
£2,400 Union of South Africa 5 % Stock (1950–70)	2,484 4 0	
(*Market value 31st December, 1931, £101,577 18s. 6d.*)	2,436 4 0	
		112,663 11 5
„ Cash in Hands of Local Centres on 30 Sept., 1931		1,068 8 7
„ Cash:—		
At Bank (Petty Cash and Wilde Benevolent Fund)	340 6 0	
In hands of Banks abroad	1,386 9 11	
In hands of Secretary	205 15 4	
		1,932 11 3
		£201,998 0 10

ERNEST LEETE,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1931, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

19th April, 1932.

ALLEN, ATTFIELD & Co., *Auditors*,
Chartered Accountants,
24, Martin Lane, Cannon Street, E.C. 4.

Dr. SALOMONS SCHOLARSHIP TRUST FUND (Capital). Cr.

	£ s. d.		£ s. d.
To Amount (as per last Account)	2,155 14 10	By Investments (at cost):—	
		£1,528 5s. 1d. New South Wales 5 % Stock (1935–55)	1,585 1 4
		£500 Cape of Good Hope 3½ % Stock (1929–49)	570 13 6
	£2,155 14 10		£2,155 14 10

Dr SALOMONS SCHOLARSHIP TRUST FUND (Income). Cr.

	£ s. d.		£ s. d.
To Amount paid to Scholars in 1931	100 0 0	By Balance (as per last Account)	26 0 5
,, Balance carried to Balance Sheet*	19 18 7	,, Dividends received in 1931	93 18 2
	£119 18 7		£119 18 7

Dr. DAVID HUGHES SCHOLARSHIP TRUST FUND (Capital). Cr.

	£ s. d.		£ s. d.
To Amount (as per last Account)	2,000 0 0	By Investment (at cost):—	
		£2,045 Metropolitan Water Board (Staines Reservoirs) 3 % Guaranteed Debenture Stock (1922 or after)	1,998 15 0
		,, Balance carried to Balance Sheet*	1 5 0
	£2,000 0 0		£2,000 0 0

Dr. DAVID HUGHES SCHOLARSHIP TRUST FUND (Income). Cr.

	£ s. d.		£ s. d.
To Amount paid to Scholars in 1931	100 0 0	By Balance (as per last Account)	33 18 10
		,, Dividends received in 1931	61 7 0
		,, Interest received in 1931	0 0 6
		,, Contribution from Institution	4 13 8
	£100 0 0		£100 0 0

Dr. PAUL SCHOLARSHIP FUND (Capital). Cr.

	£ s. d.		£ s. d.
To Amount (as per last Account)	1,000 0 0	By Investment (at cost):—	
		£625 4 % Funding Loan (1960–90)	500 0 0
		£518 3s. 8d. Central Electricity Board 5 % Debenture Stock (1950–70)	500 0 0
	£1,000 0 0		£1,000 0 0

Dr. PAUL SCHOLARSHIP FUND (Income). Cr.

	£ s. d.		£ s. d.
To Balance (as per last Account)	20 11 8	By Dividends received in 1931	53 14 5
,, Amount paid to Scholars in 1931	50 0 0	,, Donation received from Mr. R. W. Paul ..	20 11 8
,, Balance carried to Balance Sheet*	3 14 5		
	£74 6 1		£74 6 1

* Included in the total of £346 12s. 6d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	3,049 16 2	By Investments (at cost):—	
		£1,308 London and North Eastern Railway 4 % First Guaranteed Stock	1,744 3 11
		£100 London County 3½ % Consolidated Stock (1929 or after)	101 8 6
		£250 New South Wales 4 % Stock (1942–62)	251 6 0
		£500 5 % War Stock (1929–47)	501 9 3
		£381 15s. 1d. 4 % Funding Loan (1960–90)	300 0 0
		£200 3½ % Conversion Stock (1961 or after)	151 8 6
	£3,049 16 2		£3,049 16 2

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Balance carried to Balance Sheet*	200 4 7	By Balance (as per last Account)	83 0 6
		,, Dividends received in 1931	113 18 6
		,, Interest do. do.	3 5 7
	£200 4 7		£200 4 7

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,700 0 0	By Investment (at cost):—	
		£2,000 5 % War Stock (1929–47)	1,700 0 0
	£1,700 0 0		£1,700 0 0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grants made in 1931	112 10 0	By Balance (as per last Account)	75 0 0
,, Balance carried to Balance Sheet*	62 10 0	,, Dividends received in 1931	100 0 0
	£175 0 0		£175 0 0

PAGE PRIZE FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	100 19 5	By Investments (at cost):—	
		£50 5 % War Stock (1929–47)	50 19 5
		£51 16s. 4d. Central Electricity Board 5 % Debenture Stock (1950–70)	50 0 0
	£100 19 5		£100 19 5

PAGE PRIZE FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Cost of Prize awarded in 1931	4 15 0	By Balance (as per last Account)	1 0 1
,, Balance carried to Balance Sheet* ..	1 6 11	,, Dividends received in 1931	5 1 10
	£6 1 11		£6 1 11

THORROWGOOD SCHOLARSHIP TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,000 0 0	By Investment (at cost):—	
		£1,005 Agricultural Mortgage Corporation 5 % Debenture Stock (1959–89)	1,000 0 0
	£1,000 0 0		£1,000 0 0

THORROWGOOD SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1931	31 5 0	By Balance (as per last Account)	38 2 0
,, Balance carried to Balance Sheet* ..	57 2 0	,, Dividends received in 1931	50 5 0
	£88 7 0		£88 7 0

* Included in the total of £346 1s. 6d. shown on the Liabilities side of the Balance Sheet.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1931.

Dr. EXPENDITURE. **Cr.** INCOME.

Expenditure	£ s. d.	Income	£ s. d.
To Grants	1,870 7 6	By Dividends on Investments	821 3 6
,, Printing, Stationery, Bank Charges, Postages, etc.	21 19 5	,, Interest	26 16 6
,, Unexpended Balance carried to Balance Sheet	2,124 13 9	,, Annual Subscriptions	808 11 6
		,, Donations of £5 and over	1,206 8 5
		,, Donations under £5	1,054 0 9
		,, Legacy from the late Mr. E. Garcke	100 0 0
	£4,017 0 8		£4,017 0 8

BALANCE SHEET, 31ST DECEMBER, 1931.

Dr. LIABILITIES. **Cr.** ASSETS.

Liabilities	£ s. d.	£ s. d.	Assets	£ s. d.	£ s. d.
To Capital Account:—			By Investments (Capital), at cost:—		
As per last Balance Sheet	£14,242 8 4		£961 7s. 7d. Cape of Good Hope 3 % Stock (1933–43)	950 0 0	
Amount transferred from Income in 1931	3,569 8 10		£593 1s. 7d. New South Wales 3 % Stock (1935)	600 0 0	
		17,811 17 2	£420 London and North Eastern Railway 4 % First Preference Stock	503 18 3	
,, Income and Expenditure Account:—			£450 London, Midland and Scottish Railway 4 % Debenture Stock	551 0 9	
As per last Balance Sheet	£4,094 9 8		£750 East Indian Railway 3½ % Debenture Stock	737 18 0	
Unexpended Balance in 1931	2,124 13 9		£300 London, Midland and Scottish Railway 4 % Guaranteed Stock	333 11 6	
	6,219 3 5		£500 New Zealand 3½ % Stock (1940)	486 18 6	
Less amount transferred to Capital in 1931	3,569 8 10		£500 Canada 3½ % Stock (1930–50)	478 16 0	
		2,649 14 7	£5,800 5 % War Stock (1929–47)	5,783 6 1	
,, Grants authorized but not yet disbursed		72 0 0	£350 New South Wales 4 % Stock (1942–62)	336 18 6	
,, Sundry Creditors		55 6 11	£2,128 8s. 6d. 4 % Funding Stock (1960–90)	1,624 2 0	
,, Subscriptions and Donations received in advance		12 2 0	£3,295 3½ % Conversion Stock (1961)	2,512 11 10	
			£450 Commonwealth of Australia 5 % Stock (1945–75) ..	438 16 0	
			£450 Tynemouth Corporation 5 % Stock (1947–57) ..	457 7 3	
			£950 Agricultural Mortgage Corporation 5 % Debenture Stock (1959–89)	988 5 6	
			£1,000 Southern Railway 5 % Redeemable Guaranteed Preference Stock (1957)	1,028 7 0	
			(*Market value* 31*st December*, 1931, £15,470 *os. od.*)		£17,811 17 2
			,, Investment (Income) at cost:—		
			£1,000 Southern Railway 5 % Guaranteed Preference Stock ..	1,000 3 0	
			(*Market value* 31*st December*, 1931, £850 *os. od.*)		
			,, Sundry Debtors	22 3 0	
			,, Cash:—		
			At Bank	£1,753 10 7	
			In hand	13 6 11	
				1,766 17 6	
	£20,601 0 8			£20,601 0 8	

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Banks.

[illegible] April, 1932.

JAS. ATTFIELD, F.C.A.
Honorary Auditor.

RECENT DEVELOPMENTS IN CATHODE-RAY OSCILLOGRAPHS.

By A. B. Wood, D.Sc.

(*Paper first received* 18*th September, and in final form* 1*st December*, 1931; *read before the* Meter and Instrument Section *5th February*, 1932.)

Summary.

The paper deals briefly with some of the more important developments in design and use of cathode-ray oscillographs. Methods of increasing the photographic or recording sensitivity are first considered, particular attention being given to (*a*) focusing the cathode-ray stream, (*b*) increasing the sensitivity of the photographic film, (*c*) the use of phosphorescent materials as a means of increasing photographic sensitivity and of facilitating "external" photography, and (*d*) increasing the exciting voltage and consequently the kinetic energy and penetrating power of the cathode rays. With regard to (*d*), particular attention is paid to Lenard's observations on the penetrating power of high-velocity cathode rays and the application of his results to the design of high-voltage oscillographs fitted with a "window" for direct external photography.

Referring to the technique of recording by cathode rays, consideration is given to the various methods of generating a "time" axis and to methods of voltage subdivision. The paper concludes with a section dealing with the recording of isolated electrical impulses.

(1) Introduction.

In a paper* communicated to the Institution in 1924, attention was drawn to the growing importance of cathode-ray oscillographs. Three typical forms were described and consideration was given to the questions of electrostatic, electromagnetic and photographic sensitivity. Since that time these three forms of oscillograph have been used extensively, both in routine commercial work and in research.

This increased use of the cathode-ray oscillograph has naturally led to improvements in design and technique. It is the purpose of this paper to draw attention to a number of these improvements and to indicate as far as possible some of the more promising lines of future development.

In view of the fact that the medium-voltage oscillograph mentioned in the previous paper can now be used for direct photography with exciting potentials as low as 500 or 600 volts and for visual observation at even lower potentials, no useful purpose would be served by drawing the distinction between low-, medium-, and high-voltage oscillographs. A more natural classification is simply high- and low-voltage oscillographs, the former working over a range of 10 kV upwards and the latter over a range 10 kV downwards. The former type usually, but not necessarily, employ a cold cathode, whilst the latter invariably use a hot cathode.

The line of progress has been concerned mainly with methods of improving the photographic conditions in the cathode-ray oscillograph. This improvement has been achieved in various ways, direct and indirect. The first part of the paper will deal more particularly with some of these methods. The extended use of the cathode-ray oscillograph in the study of impulsive and very high-frequency phenomena such as those encountered in lightning discharges, in wireless transmission, and in surges in high-power lines, has necessarily evoked much ingenuity on the part of engineers and physicists to devise suitable timing circuits for recording. When it is considered that non-periodic electrical impulses of duration not exceeding 10^{-6} sec. are recorded as a matter of routine, it will be realized to what degree of perfection this timing is carried out. The latter part of the paper will deal with some of the more important methods of generating a time scale and in timing unexpected impulses (for example, lightning flashes) of short duration. Some consideration will also be given to various forms of potential dividers, more particularly those required in recording high-voltage phenomena exceeding the voltage-deflection limits of the oscillograph.

* See References (1) and (2).

(2) Methods of Increasing Recording Sensitivity. "Internal" and "External" Photography.

The electrostatic and electromagnetic sensitivity of a cathode-ray oscillograph are defined simply by the linear dimensions of the apparatus and the voltage used to accelerate the cathode rays. The photographic sensitivity is, however, much more difficult to control. The efficiency of an oscillograph from the standpoint of its practical utility is dependent largely on its photographic sensitivity. It is consequently a matter of importance to consider the various possible methods of increasing this sensitivity. In the papers already referred to the following methods were discussed:—

(*a*) Focusing of the cathode stream and, in the case of the hot-cathode oscillograph, increasing the emission of the cathode.
(*b*) Improvement of the photographic film.
(*c*) Use of phosphorescent materials to increase, or otherwise facilitate, the photographic effect.
(*d*) Increasing the accelerating voltage.

It is convenient to deal with them in this order again.

(*a*) *Focusing the Cathode Stream.*

In the paper* read before the Physical Society of London in 1923, various methods, mechanical, electrostatic, and electromagnetic, of focusing a beam of cathode rays were described. Of these the electrostatic method, using a Wehnelt cylinder surrounding the cathode, was considered to give the best results. When a very small, intense recording spot was required, however, it seemed doubtful whether focusing was an advantage as a means of increasing intensity. The

* See Reference (2).

beam of rays appeared to consist of a heterogeneous bundle of fine pencils varying in intensity within wide limits. When one of these fine, intense pencils was deflected through the pinhole tube a brilliant recording spot was obtained which usually proved sufficient for high-speed recording. An ideal focusing device would of course converge all such fine pencils of rays into a single small spot, but that is somewhat difficult to carry out in practice. Using a modified form of Western Electric cathode-ray tube, M. von Ardenne* has recently employed the Wehnelt cathode with considerable success. Instead of connecting the Wehnelt cylinder to one end of the filament, or leaving it in a " floating " condition, he finds that a negative voltage applied to it produces a good initial concentration of the cathode beam which passes through a 2 mm dia. aperture in the anode without loss due to screening. Divergence of the beam after passing the anode is prevented by nullifying the space charge in the tube. M. von Ardenne states that this latter condition is effected by the presence of a trace of a rare gas in the vacuum " by the ionization of which a considerable number of positive ions is produced, causing the electrostatic repulsion due to the space charge to be outweighed by the electrodynamic attraction of the convection currents moving approximately parallel to one another in the ray." Whether or not this is the true explanation of the focusing action, the spot obtained is small and brilliant. A number of other observers have used the Wehnelt cathode with success, for example S. Watanabe† and R. H. George.‡ This method is, of course, particularly applicable to low-voltage, hot-cathode oscillographs.

The electromagnetic method of focusing has been used by W. Rogowski§ in a cold-cathode oscillograph operated at 60 kV. Max Knoll considered, however, that focusing is unnecessary at these high voltages, when the cathode rays have a very high velocity (e.g. at 64 kV $1{\cdot}5 \times 10^{10}$ cm per sec., i.e. half that of light).

In connection with the question of focusing cathode rays emitted from an electrically heated filament a difficulty may arise on account of the strong magnetic field at the surface of emission. In the case of a thin wire this field may reach a high value sufficient to produce a large bending of the track of a cathode ray as it leaves the filament, for example with a filament 0·005 cm radius carrying 1 ampere the field strength at the surface is 40 gauss, which is sufficient to give a large initial deflection to an electron at the instant of emission. The path of a cathode ray is therefore dependent not only on the type of focusing device employed but also on the state of the magnetic field (due to filament current) at each element of the surface of the filament. A close examination of the cathode stream leaving an oxide-coated filament surrounded by a Wehnelt cylinder reveals this effect very clearly. Inside the conical beam isolated " rays " having curved paths may be seen, the curvature and direction of these paths varying considerably. Reversal of filament current produces a marked change in the appearance of the beam. One method of overcoming this difficulty may be to use an indirectly heated emitting surface. For example, the use of a filament with an oxide coated sheath, as in a.c. valves, might prove a satisfactory solution. Perhaps the same result could be achieved by coating a filament with a *thick* layer of calcium or barium oxide. For example, if we assume the filament to have a diameter of 0·004 in. and the coating (or sheath) 0·020 in. dia., this would reduce the strength of the magnetic field at the emitting surface to 20 per cent of its value at the surface of the bare filament. This assumes, of course, that the current flowing through the heated oxide layer is negligible.

Another alternative is to use a filament wound non-inductively with the turns as close together as possible. This method has given good results in practice.

Apart from such methods of focusing, further increase of intensity of the beam in hot-cathode tubes may be obtained by increasing the temperature of the filament. The thermionic emission of a filament increases extremely rapidly with filament current,* small increases of current producing large increases of filament temperature and thermionic emission.

Until recently the upper limit appeared to be fixed by the fusing temperature of the filament (coated with oxides of alkaline earths, Ca, Ba, and Sr), but W. Rogowski† has produced a tube with an extremely high cathode emission by the use of a *molten* cathode. The tube will operate for several hundred hours without appreciable variation in the cathode-ray emission, owing to the fact that the surface of the molten cathode is continuously changing, thus providing a fresh, clean surface for emission of electrons. The brilliance of the phosphorescent screen in Rogowski's experiments was so great that it was actually considered as a means of producing light! The oscillograph was consequently adopted for both " internal " (or direct) photography, or for " external " photography, the luminous image being focused by a camera lens.

With a view to increasing the electron emission at lower temperatures, a large amount of work has been done recently in connection with the development of oxide-coated filaments, in particular with barium-oxide coating, for use in valves. The electron emission from a barium-oxide-coated filament is very much greater than that of a bare filament at the same temperature, and Hodgson‡ states that he has not been able to detect any change in the amount of barium present in a filament after 1 000 hours' running. Such a filament should therefore prove very suitable for a cathode-ray oscillograph.

(b) *Photographic Film.*

The sensitivity of photographic films to cathode rays bears practically no relation whatever to their sensitivity to light. The point of importance is to provide a sensitive layer which contains a large proportion of sensitive silver granules *which can be reached by the cathode rays.* The difficulty of selecting a suitable sensitive photographic plate only arises in the case of low-voltage cathode rays. At voltages of the order of 10 000 upwards the rays are sufficiently penetrating to affect the lower layers of silver bromide in an ordinary photo-

* See Reference (8).
‡ *Ibid.*, (5).
† *Ibid.*, (4).
§ *Ibid.*, (6).

* See Reference (7).
† *Ibid.*, (8).
‡ *Ibid.*, (7).

graphic film. With lower-velocity rays, however, generated at voltages below 5 000, the absorption in the gelatine is very rapid and only surface layers of silver bromide are affected. The thickness of film on an ordinary plate is approximately 10^{-3} cm, which is just penetrated by cathode rays at 30 000 volts, whilst rays at 3 000 volts can only reach a depth of 1 per cent of the thickness.

Half-tone plates (manufactured for engraving work) are an improvement on ordinary plates. The film is much thinner and the proportion of silver to gelatine is increased. They have a very fine grain and can be developed, fixed, washed, and dried more quickly than ordinary plates. The blackness of the developed image is, however, disappointing but may, of course, be intensified. For recording at low and moderate speeds these plates are fairly satisfactory.

A very sensitive plate of the Schumann type is made by Hilgers. This plate, the Hilger-Schumann plate, contains approximately 100 times the silver-gelatine ratio that an ordinary plate does. With these plates good single-traverse records have been made with a cathode-ray voltage as low as 500 volts. The plates are, however, rather expensive and require care in handling during development and drying.

Even greater sensitivity is obtained by eliminating the gelatine almost completely. Plates of this kind have been prepared for the author by Mr. Jackson, of the Admiralty Research Laboratory, by depositing silver iodide on glass. These plates show a remarkably high sensitivity to low-voltage cathode rays, a single traverse at 100 000 cycles per sec. giving a good trace with a cathode-ray exciting voltage as low as 600 volts. The difficulty of handling these plates is not appreciably greater than that experienced with Schumann plates.

An alternative to the Schumann plate is known as the "Schumannized" plate. These are ordinary plates converted by a somewhat delicate operation into Schumann plates by dissolving out the gelatine.* The ordinary plates are immersed for 4 hours in a bath of sulphuric acid (100 cm^3 acid at 66° F. to 1 litre water),† carefully withdrawn, washed in gently running water for 30 minutes, and dried. Such plates contain only a very thin layer of emulsion, uniformly distributed, and are poor in gelatine. Aston‡ found that some of these plates, made from half-tone plates, were even more sensitive than Schumann plates, and gave also a cleaner background and sharper definition. The plates are developed in ordinary hydroquinine developer diluted to half strength, sufficient bromide being added to bring the time of development to about 1 minute. Schumannized plates deteriorate more rapidly than ordinary plates and should be used fresh to get the best results.

High-velocity cathode rays will, as already stated, record well on ordinary plates. It should be quite possible, however, to obtain a further increase of photographic sensitivity, if at any time it is required, by thickening the sensitive layer and increasing the silver-gelatine ratio to absorb and utilize efficiently the whole of the cathode-ray stream.

* See References (9) and (10).

† Aston used battery acid of density 1·225 diluted with an equal volume of water.

‡ See Reference (10).

(c) Use of Phosphorescent Materials to Increase or Facilitate Photography.

The possibility of recording by means of the secondary effect of luminosity produced by the cathode rays falling on a phosphorescent material has always appeared attractive, and a number of observers have used this method. The chief advantage to be gained is, of course, that of external photography. In the earliest days of the Braun tube it was possible to photograph a pattern such as a Lissajous figure in which the cathode beam retraces the same track a large number of times. The cumulative effect of the successive traverses of the luminous spot ultimately produced sufficient effect on a photographic layer (bromide paper or film) placed in close contact with the external glass surface of the phosphorescent screen.

An attempt to make use of this luminous effect *in addition* to the direct photographic effect was made by the author* in 1920. A Schumann plate was prepared with a small proportion of calcium tungstate mixed in the sensitive silver-bromide layer. Calcium tungstate phosphoresces with a light rich in ultra-violet, and Schumann plates are extremely sensitive to ultra-violet light as well as to the direct action of cathode rays. A definite improvement was noticed when very small proportions of calcium tungstate were used. Excess of this phosphorescent material, however, produced a marked *decrease* in sensitiveness. This is explained by the fact that calcium tungstate is a heavy material which easily stops the cathode rays and consequently reduces the direct photographic action.

R. Terroux† has suggested that the indirect luminous effect might be comparable with the direct photographic effect of the rays, thence inferring that an oscillograph with external photographic arrangements would have equal photographic sensitivity to one fitted for internal "direct" photography. Terroux employed in his experiments a simple cold-cathode tube excited from a spark coil. The cathode rays were directed on a quartz window coated on the vacuum side with willemite (zinc ortho-silicate), quartz being used to transmit any ultra-violet light in the phosphorescence. Exposures ranging between 1 sec. and 0·01 sec. were made. The blackening was such that Terroux estimated that an average exposure of 10^{-4} sec. would still have an effect. No comparison was made, however, between the "direct" effect and the "indirect luminous effect" of the cathode rays.

In order to test this important point the author made the experiment, some years ago, of traversing a beam of 4 000-volt cathode rays across a Schumann plate one-half of which was covered with a quartz plate (0·5 mm thick) coated with a thin layer of calcium tungstate, a material which phosphoresces with a light rich in ultra-violet rays and photographically very active. One-half of the plate was therefore exposed to the direct action of the cathode rays and the other half to the luminosity of the phosphorescent screen. The records showed conclusively that the direct effect was many times greater than the luminous effect, the former giving intensely black records whilst the record made by the latter was hardly visible. In comparing this result with Terroux's

* See Reference (1).

† *Ibid.*, (11).

observations it must be remembered, of course, that he used a cold-cathode tube with high-voltage rays, whereas in the above experiment the exciting voltage was relatively low. W. Rogowski,* however, has also compared "direct" and "luminous" effects with a high-voltage oscillograph, his results confirming the author's.

The advantages of external photography by the phosphorescent-screen method in certain circumstances outweigh other considerations. Where the speed of recording is not too great, and the cathode stream is sufficiently intense, good records may be obtained in a single traverse. M. von Ardenne† has recently proved very successful in the design of a tube of this kind. Using a Wehnelt cathode and the focusing arrangements already described, he has succeeded in obtaining small recording "spots" which give good records of audio-frequency phenomena. He uses a camera lens of aperture F/2·5, or F/1·5 if required, to form an image of the phosphorescent transient on a super-sensitive photographic plate. He uses calcium tungstate or willemite as the phosphorescent material for the screen, and anode potentials of 1 000 to 2 000 volts. This tube is a distinct advance on previous forms of cathode-ray tube of similar type. It has many applications in the faithful recording of audio-frequency phenomena and in the recording of transients, provided the frequency is not too high. As a matter of interest, it may be mentioned that the tube worked equally well with either d.c. or a.c. heating of the filament. This is achieved by the simple expedient of looping the filament leads to neutralize the magnetic field due to the filament.

W. Rogowski and E. Ruhlemann‡ have measured the luminous output of the screen of a high-voltage tube. At 55 kV the value found was 35 lumens per watt, using a Buchler zinc-sulphide screen. They consider that other phosphorescent materials are not likely to be better than this.

(*d*) *High-Voltage Oscillographs. "Internal" and "External" Photography.*

(i) *Internal Photography.*—The kinetic energy, and consequently the square of the velocity v of the cathode rays, is directly proportional to the accelerating potential V

i.e. $$\text{Kinetic energy} \propto v^2 \propto V$$

The depth of penetration d of the rays into a photographic layer§ is proportional to v^4,

i.e. $$d \propto v^4 \propto V^2$$

On these grounds it is obvious that one of the most powerful and direct methods of increasing photographic sensitivity is the use of large accelerating voltages. This was appreciated by A. Dufour,‖ who constructed the first effective high-voltage oscillograph. His lead has been followed by numerous Continental and American workers, who have realized its great value in the study of transient phenomena encountered in high-voltage power circuits.

Of course the electrostatic voltage-sensitivity δ of an oscillograph is inversely proportional to the cathode potential, i.e.

$$\delta = \frac{k}{V} \text{ cm per volt}$$

where k is a constant depending on the linear dimensions of the oscillograph,* which implies a small electrostatic sensitivity when V is large.

When high-voltage phenomena are to be recorded, however, this question of voltage sensitivity is of negligible importance. The gain in photographic sensitivity obtained by increasing V outweighs all other considerations. Two high-voltage oscillographs are represented diagrammatically in Figs. 1(*a*) and 1(*b*). Fig. 1(*a*) is a representation of Dufour's oscillograph, using a cold cathode, whilst Fig. 1(*b*) is one due to Rogowski† in which a hot cathode is employed. In both these oscillographs the applied potential is in the neighbourhood of 60 000 volts. A photograph of a 500-volt (and upwards) oscillograph designed by the author is shown in Fig. 1(*c*) for comparison. Modified forms of the high-voltage oscillographs have been used by R. H. George‡ in America and H. Mathias and M. Knoll§ and others on the Continent. All these workers agree that the photographic effect at high generating voltages is so great that almost any speed of recording is possible. Thus W. Rogowski and E. Flegler‖ have obtained

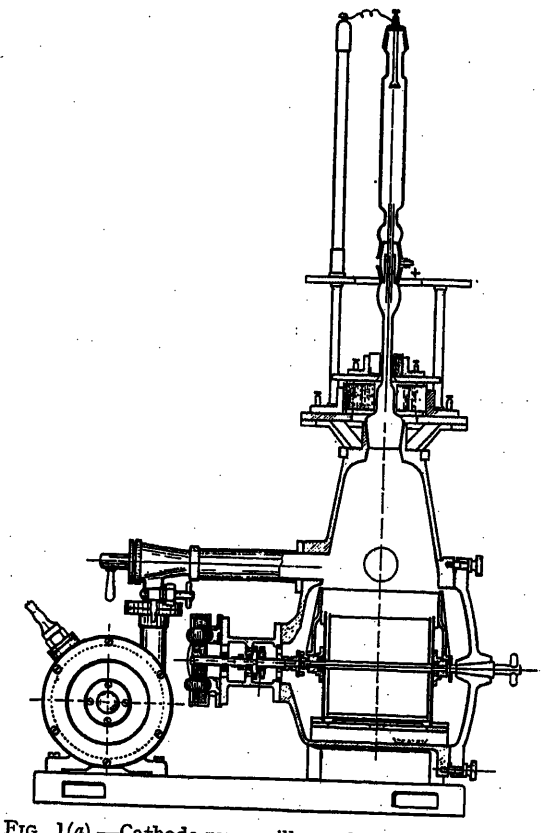


FIG. 1(*a*).—Cathode-ray oscillograph due to A. Dufour (cold cathode, 60 kV).

* See Reference (8).
‡ *Ibid.*, (8). § *Ibid.*, (1). † *Ibid.*, (3). ‖ *Ibid.*, (12).

* See Reference (1).
‡ *Ibid.*, (14). § *Ibid.*, (15). † *Ibid.*, (13). ‖ *Ibid.*, (16).

oscillograph records which indicate an average recording speed of 63 000 km per sec., nearly one-quarter the velocity of light. At this enormous recording speed oscillations of frequency 10^8 per second and transients having a duration of the order of 10^{-9} second have been recorded. It will be seen, therefore, that the upper frequency-limit of recording is not likely to be set by the photographic effect, but rather by the finite velocity of the cathode rays. This latter point has been considered in some detail by J. T. MacGregor-Morris and R. Mines,* who have dealt with the theoretical aspect of the problem of high-frequency deflection of cathode rays of known velocity passing between electrostatic deflecting plates of known dimensions. At very high frequencies also it becomes a matter of considerable importance to allow for the inductance and capacitance of the leads

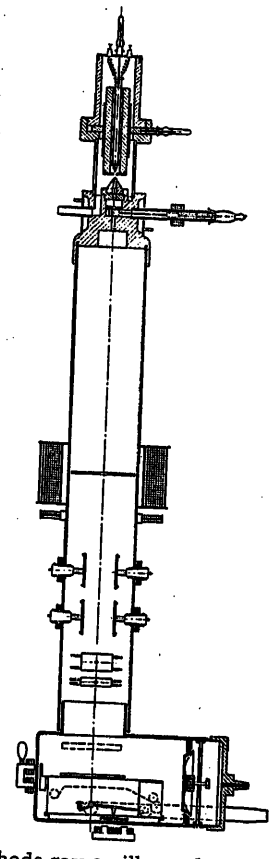


FIG. 1(*b*).—Cathode-ray oscillograph due to W. Rogowski (hot cathode, 60 kV).

and deflecting plates of the oscillograph itself. Great care is required at the highest frequencies to avoid trouble due to resonance in the oscillograph circuit. It is not unlikely that the upper frequency of recording will be set by such considerations.

(ii) *External Photography. Use of Lenard Window.*—In a paper read before the Physical Society of London in 1923† reference was made to an attempt "which is being made to develop a sealed form of cathode-ray oscillograph with external photographic arrangements. For this purpose experiments are in progress with various focusing devices, so as to obtain an intense beam of cathode rays which will give an appreciable photographic effect after passage through a window." It was intended to employ cathode rays of voltage 4 000 to 5 000 and "windows" of aluminium foil (or leaf) or thin mica slips covering a slit. The cathode rays would oscillate along this slit, under the impressed deflecting voltage, and after passage through the window would fall on a photographic film revolving at the desired speed. Subsequent calculation soon showed, however, that such experiments

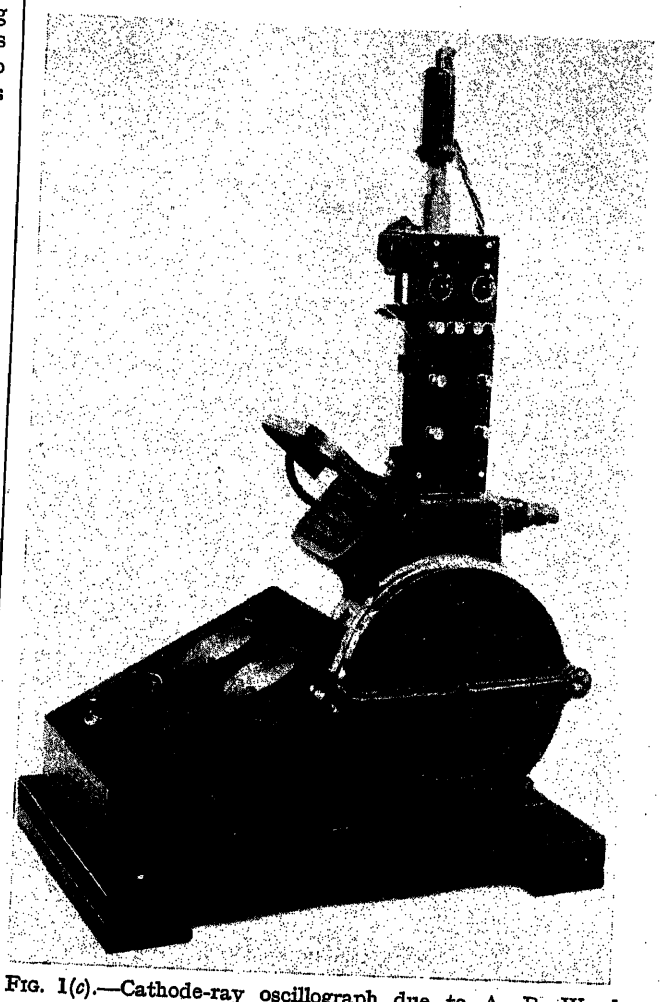


FIG. 1(*c*).—Cathode-ray oscillograph due to A. B. Wood (hot cathode, 1 000 volts).

were likely to fail, for the minimum thickness of a window which would withstand atmospheric pressure applied to the slit would completely stop such low-voltage cathode rays. Of course there still remains the possibility of using extremely thin foil (aluminium leaf $0{\cdot}8 \times 10^{-4}$ cm thick) if the camera side of the foil were evacuated (to 1 or 2 mm pressure) simultaneously with the cathode-ray tube. No opportunity has hitherto been afforded for such an experiment.

If cathode rays of much higher velocity are used, corresponding to 60 kV, for example, the "window" at once becomes a practical possibility. It is profitable at

* See Reference (17).

† *Ibid.*,

this stage to deal with Lenard's observations on the absorption and loss of velocity of cathode rays on passing through varying thicknesses of aluminium.

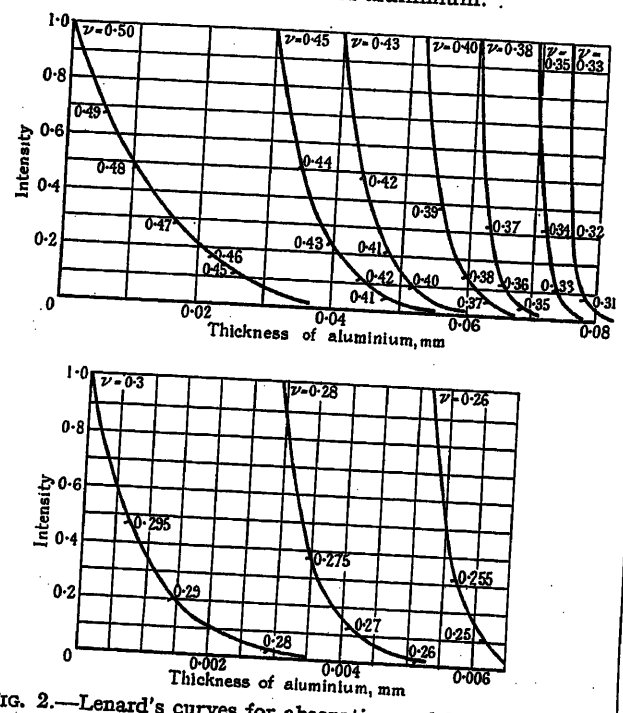


FIG. 2.—Lenard's curves for absorption and loss of velocity of cathode rays in aluminium.

Lenard's absorption curves are represented graphically* in Fig. 2. Each curve commences at the top of the diagram with an arbitrary value of unit intensity. The velocity v is indicated at various points along the curve. When the values of intensity become inconveniently small a fresh curve is started from unit intensity. The range of cathode-ray velocities covered by the curves is 0·25 to 0·50 times the velocity of light

* See Reference (18).

(3 × 10^{10} cm per sec.), corresponding to accelerating potentials in the range 15 to 63 kV approximately. For the sake of convenience in studying Lenard's absorption curves, Fig. 3, showing the relation between cathode-ray velocity and applied voltage, is reproduced.* The

TABLE.

Voltage	Initial velocity × c (c = 3 × 10^{10} cm/sec.)	Thickness of aluminium required to halve intensity	Emergent velocity × c
kV		mm	
—	0·99	2·80	
205	0·90	0·35	0·975
163	0·80	0·17	0·86
125	0·70	0·07	$0·75_4$
91	0·60	0·03	0·66
63	0·50	0·01 (10μ)	$0·57_4$
51	0·45	$0·005_5$ (5·5μ)	$0·48_2$
41	0·40	0·003 (3μ)	0·44
32	0·35	0·002 (2μ)	$0·39_3$
23	0·30	0·0007 (0·7μ)	$0·34_4$
16	0·25	0·00025 (0·25μ)	0·296
			0·246

velocity v, expressed as a ratio in terms of c the velocity of light, is calculated from the relation

$$v = 6\sqrt{V} \times 10^7 \text{ cm per sec.}$$

or

$$\frac{v}{c} = 2\sqrt{V} \times 10^{-3},$$

where $c = 3 \times 10^{10}$ cm per sec.

This relation, of course, only holds over a limited

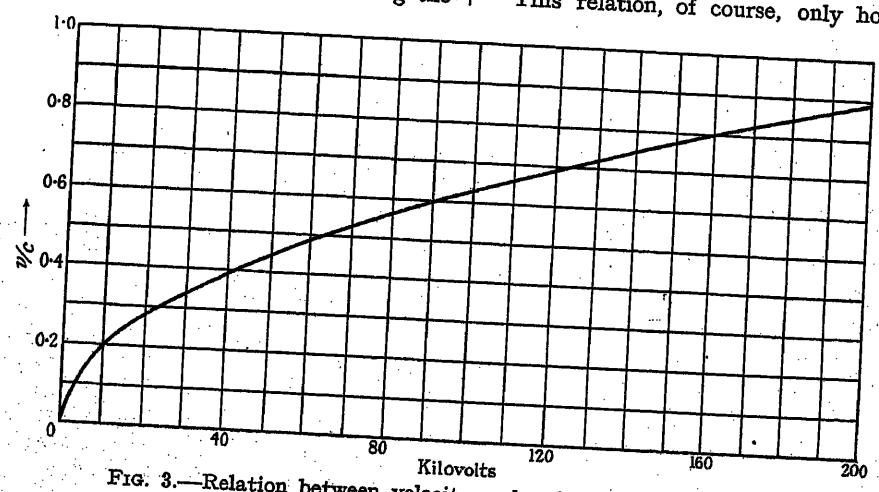


FIG. 3.—Relation between velocity and voltage of cathode rays.

$v = 6\sqrt{V} \times 10^7$ cm/sec.
$= 2\sqrt{V} \times 10{-}3 \times$ velocity of light (c).
i.e. $v/c = 2\sqrt{V} \times 10{-}3$ (approx.).

velocity range, but may be regarded as approximately correct over the range 0 to 0·9c shown in the diagram.

The above table, derived from curves such as those shown in Fig. 2, gives the thickness of aluminium required

* See Reference (19).

to reduce the intensity of the cathode-ray stream to half its initial value. A column is added to indicate the emergent velocity of the cathode rays.

From this table and Lenard's absorption curves it is a relatively simple matter to determine the maximum permissible thickness of aluminium to use for a cathode-ray window when the voltage of the rays is known, or alternatively to calculate the voltage of the rays for a given thickness. Thus, for aluminium leaf of thickness $0{\cdot}5\mu$ ($0{\cdot}5 \times 10^{-3}$ mm) the voltage necessary, if a loss of intensity of 50 per cent is not to be exceeded, is approximately 20 000 volts. It is evident then that low-voltage cathode rays (of the order 5 000 volts) are out of the question as regards external photography through a window* (but see page 48). A glance at the curves and the table reveals, however, that the penetrating power of the rays rapidly increases with voltage. For example, at a voltage of 63 kV the rays can penetrate 10μ (0·01 mm) aluminium with only 50 per cent loss of intensity. It will be noted that the diminution of velocity is quite small in all the cases shown in the table; the energy of the cathode rays which emerge therefore remains practically unchanged. Now aluminium foil of thickness 10μ mounted on a supporting grid of reasonably small mesh is capable of withstanding atmospheric pressure without collapsing and, as we have seen, will transmit 50 per cent of 63-kV cathode rays with almost undiminished velocity. Under such conditions, therefore, " external " should be almost as good as " internal " photography.

The first successful oscillograph to employ external photography through a Lenard window appears to be due to Max Knoll† and his collaborators at the high-voltage laboratories of the Technische-Hochschule, Berlin. A window of aluminium 7 to 10μ thick ($1\mu = 10^{-3}$ mm) or of cellon 16μ thick and 4×6 cm^2 in area was supported on a grid of steel ribbon with a close-knit mesh of phosphor-bronze gauze stretched over it. The meshes of the wire gauze were small compared with the breadth of the lines of the oscillograph record, the area of each mesh being 0·003 mm^2. The mesh of the steel-ribbon grid was about 1 cm^2, the ribbon of course being arranged edgewise so as to cast the minimum amount of shadow on the photographic plate. The exciting voltage used was 75 kV, the current being limited to 1 mA. Such high-voltage rays can, as we have seen from Lenard's curves, penetrate 10μ aluminium foil without appreciable loss of intensity or velocity. Consequently the blackness of the photographic trace is practically as good as that obtainable inside the vacuum. Knoll's oscillograph records obtained through this window show practically the same sharpness of line as high-vacuum photographs. On account of the scattering of the cathode rays the fine-wire gauze does not cast a definite shadow and is consequently imperceptible in the oscillograph record. The steel-ribbon grid, 1 cm square, can be seen as a faint shadow which serves admirably as a co-ordinate system.

Using this method, Knoll has recorded oscillations of frequency 10^8 per sec., the maximum recording speed in this case being 5 000 km per sec. The maximum sensitivity of the oscillograph reached 0·1 mm per volt at an exciting potential of 75 kV. Knoll's work demonstrates the great advantages of using high-voltage cathode rays when voltage sensitivity is unimportant. The use of a Lenard window and external photographic arrangements simplifies and increases the speed of working and eliminates many of the difficulties inherent in high-vacuum photography. It should be mentioned, however, that the " window " method still requires a high-vacuum pump in constant operation, for thin metal and cellon foils are porous to air. Small air-leaks through pores and small holes may, however, be easily kept " in hand " by a good quick-acting vacuum pump. This type of oscillograph possesses obvious advantages also when continuous records are required over long periods. Thus Knoll refers to such an oscillograph working for many hours a day in a lightning observatory on Monte Generoso in Switzerland, during the whole summer of 1929, without a single disturbance of the vacuum. During a long thunderstorm it was possible to record automatically more than 1 000 oscillograms on one single film. In this connection also an interesting reference is made to a cathode-ray oscillograph fitted with a mercury barometer device by means of which films of any length could be drawn continuously from free air through the high vacuum. As Knoll remarks, external photography through a Lenard window is of great importance, for in this way the size, weight, and manufacturing costs of the oscillograph can be considerably decreased and the whole photographic process considerably simplified.

About the same time that Knoll was developing the metal-foil Lenard window oscillograph, C. M. Slack,* in America, used a Lenard tube with a thin glass window 0·005 to 0·01 mm thick and pointed out the possibility of using it as a " Lenard-ray " oscillograph. No supporting grid was used, the glass window being hemispherical to withstand atmospheric pressure. Such a shape of window of course necessitates the use of film or bromide paper fitting closely to the curved surface, otherwise the cathode-ray stream would be scattered by the intervening air.

In view of the fact that aluminium and glass have approximately the same density (aluminium 2·65, crown glass 2·4 to 2·6) they will absorb cathode rays about equally and we may consequently regard Lenard's curves reproduced in Fig. 2 as being approximately applicable to glass also. Hence if the exciting voltage of the cathode ray were raised still further, say to 160 kV instead of 75 kV used by Knoll, the thickness permissible to give 50 per cent transmission would be increased to 0·17 mm. A glass sheet of this thickness and of moderate area would support a considerable pressure. The advantage of glass over aluminium is, of course, its relatively small porosity. With such a window, a completely sealed high-voltage oscillograph should be possible and the continuous use of the vacuum pump eliminated.

The low-voltage hot-cathode oscillograph still remains

* As a matter of interest, however, it is worth noting that extremely thin metal films capable of withstanding considerable pressures are obtainable. Thus, Carl Müller (*Sitzungberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 1925, vol. 25, p. 464; also *Engineering*, 1926, vol. 121, p. 199) has prepared films of metal (gold, silver, platinum, nickel, and iron) of thickness $0{\cdot}04\mu$ (4×10^{-6} cm) of diameter 6 cm, and $0{\cdot}01\mu$ of smaller diameter. Such nickel films have been mounted (over wire gauze) as windows in discharge tubes and have resisted gas pressures equivalent to 25 cm of mercury. For comparison it may be stated that ordinary gold leaf has a thickness of $0{\cdot}08\mu$, and aluminium leaf $0{\cdot}5\mu$ approximately.

† See Reference (20).

* See Reference (21).

pre-eminent, however, where voltage-sensitivity is important. The problem of the Lenard window for this oscillograph is a difficult one, but it seems not impossible that some means will be found of dealing with it successfully. A number of avenues require exploration. For example, it may be possible to accelerate the cathode rays *after electrostatic deflection*, by the use of a high potential applied in the region between the deflecting plates and the photographic plate. It should be possible also to use windows of very thin leaf by employing a forevacuum on the camera side of the Lenard window. With such an arrangement (aluminium leaf $0{\cdot}8\mu$ thick) the pressure difference acting on the window need never exceed a few millimetres of mercury, and the percentage transmission of the cathode rays would not be excessively low (see also pages 46 and 47).

(3) The Technique of Recording by Cathode Rays.

When a cathode-ray oscillograph is employed to record rapid fluctuations in the voltage or current in a circuit, certain operations are necessary to ensure a satisfactory result. It is first of all necessary to provide a suitable time scale and means for deflecting the cathode stream in a known manner. If the electrical phenomenon to be recorded is of an impulsive or non-periodic character it may be necessary to provide an accurate timing device to ensure that the electrical impulse occurs when the cathode-ray spot is at a suitable point of its travel on the photographic plate. Another difficulty which may arise is that of recording a high-speed high-voltage effect, which renders it necessary to utilize a suitable potential-divider in the recording circuit without distorting the wave-form. During the past five or six years various ingenious methods have been introduced to deal with such operations. The impossibility of providing a universal treatment to meet all cases will be appreciated, but the large majority of oscillograms may be obtained by methods which are now fairly generally recognized. It is the purpose of this section of the paper to refer briefly to some of the more important of these methods.

(*A*) *Generation of a Time Axis.*

The time scale of an oscillogram may be derived either by the use of an auxiliary time-marking device, by driving the film, or by traversing the cathode "spot" over the photographic plate or film in a known manner. As the last two methods are in general use and appear to be the most important we shall deal with these cases only. Mechanical, electrostatic, and electromagnetic methods or combinations of these are available.

(*a*) *Mechanical Methods.*

These methods are in daily use with all forms of oscillograph and are sufficiently well known without further description here. Various authorities differ as to the limit of film speed attainable, but a linear speed of 50 or 100 metres per second may be provisionally assumed to be a safe working maximum for general purposes.

(*b*) *Electromagnetic and Electrostatic Methods.*

(i) *Sinusoidal Time-base.*—One of the simplest methods, and perhaps the earliest, is to deflect the cathode stream by means of alternating current of known frequency and good wave-form applied either to an electromagnet or to a pair of electrostatic deflecting plates, thus producing a sinusoidal oscillation of the cathode rays. This method, whilst possessing the advantage of simplicity in recording isolated electrical impulses, is obviously unsuitable for recording wave-forms of alternating currents. Even in the case of impulse recording, the resultant record requires careful analysis to transpose the sinusoidal time-deflection into a linear one. It was used by A. Dufour* to record damped oscillations in spark circuits, later by D. A. Keys† to record piezo-electric impulses, and by R. A. Watson Watt‡ to record outlines of atmospherics. Dufour generally combined this method with the mechanical method [(*a*) above]. The effect to be recorded was arranged to deflect the rays along the direction of the mechanical drive and at right angles to the axis of sinusoidal deflection.

(ii) *Linear Time-base.*—The advantages to be obtained by using a linear instead of a sinusoidal time base are self-evident. A number of very reliable methods have been devised to give a time base approximately linear. In some of these methods the cathode-ray spot is arranged to flash across the plate or screen once only at a uniform rate, whilst in others this linear deflection is repeated at regular intervals. The former method is applicable more particularly to oscillographs which are capable of recording a single traverse. The latter method is applicable to any form of oscillograph and is particularly valuable when (*a*) an electrical impulse is to be recorded and the exact instant of arrival is not known, and (*b*) a repetition phenomenon is to be observed.

(ii)$_1$ *Single Traverse.*

We shall consider first a number of methods of obtaining a single traverse of the spot at a uniform speed.

Inductance method.—If a voltage E is suddenly applied to a circuit of inductance L and resistance R [see Fig. 4(*a*)] the current i at any instant t is given by

$$i = \frac{E}{R}\left(1-e^{-\frac{R}{L}t}\right)$$

$$= \frac{E}{R}\left\{\frac{R}{L}t - \frac{R^2}{2L^2}t^2 + \text{terms containing higher powers of } t\right\}$$

Provided t is always small compared with L/R we may write

$$i = \frac{E}{L}t$$

that is, in the early stages of rise of current in the circuit the current i is a linear function of the time t. In the actual application of this method it is advantageous to use an auxiliary winding to the deflecting electromagnet (which may be an iron-core or an air-core solenoid), this winding carrying a steady current to deflect the spot off the left-hand edge of the plate. On

* See Reference (12). † *Ibid.*, (22). ‡ *Ibid.*, (23).

closing the circuit of the main deflecting magnet the spot is swept across the plate at a uniform speed to the opposite side. The maximum speed will of course be limited ultimately by the inductance of the deflecting magnet itself. At very high speeds an air-core magnet must therefore be used.

An alternative arrangement [see Fig. 4(*b*)] connects the electrostatic deflecting plates across the inductance L which in this case has a resistance negligible compared

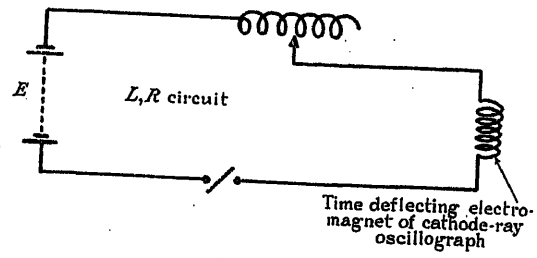


FIG. 4(*a*).

with that of the remainder of the circuit. The instantaneous voltage across the inductance L is now given by

$$v_L = Ee^{-(R/L)t} = E\left(1 - \frac{R}{L}t + \frac{R^2}{2L^2}t^2 - \text{etc.}\right)$$

or, in the case when t is small compared with L/R,

$$v_L = E\left(1 - \frac{R}{L}t\right)$$

which represents a linear fall of voltage with time across the inductance, and consequently across the deflecting plates of the oscillograph.

A transformer may in some cases provide a convenient means of continuously varying the inductance in the

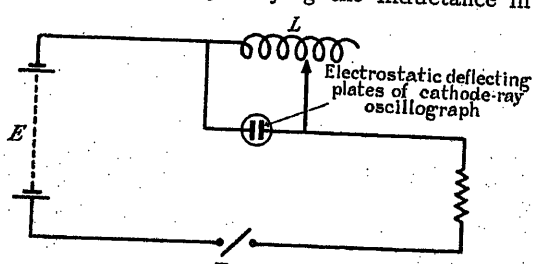


FIG. 4(*b*).

" time " circuit [see, for example, Fig. 4(*c*)]. The transformer primary P in series with the deflecting electromagnet has an effective inductance L' depending on the load on the secondary circuit

$$L' = L_0 - M\frac{i_2}{i_1}$$

(assuming perfect coupling). If, therefore, a variable resistance be connected across the secondary circuit S of small inductance, the load and hence the effective inductance of the primary may be varied over a wide range. With a short-circuited secondary the primary self-inductance is almost neutralized and the primary current rises rapidly, whilst with an open secondary the primary current is choked down by the large effective primary self-inductance.

Condenser Method.—A convenient method of producing a linear deflection with time employs a condenser of capacitance C which may be charged or discharged through a resistance R [see Fig. 4(*d*)]. In the case of a charging current, the voltage v_c across the condenser at any instant t after closing the circuit is given by

$$v_c = E(1 - e^{-t/CR})$$

which, in the case of small values of t compared with CR, reduces to

$$v_c = \frac{E}{CR}t$$

In this case also we see that the voltage across the electrostatic deflecting plates of the oscillograph increases

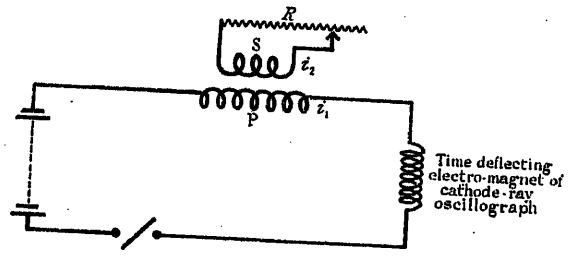


FIG. 4(*c*).

linearly with time, provided the assumed conditions are fulfilled.

At very high speeds of traverse the inductance method is not so good as the capacitance method. If iron-cored magnets are used the rate of current-rise is limited by lag in the iron, and if open air-solenoids are used there is risk of distortion due to stray fields. The condenser method is free from these disadvantages and is consequently generally used in high-speed recording.

The single-traverse method, using either inductance or capacitance, is very convenient in recording alternating-current wave-forms or single impulses. In the

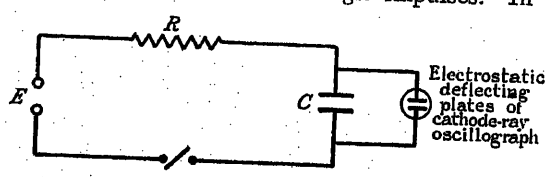


FIG. 4(*d*).

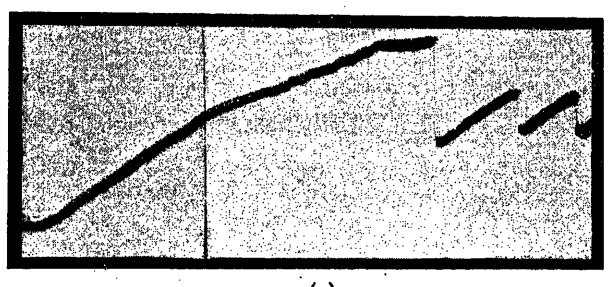
former case recording is relatively simple, a hand-operated switch being sufficient to traverse the oscillating spot across the plate. Methods of recording single impulses are considered later (see page 54).

$(ii)_2$ *Repeated Traverse.*

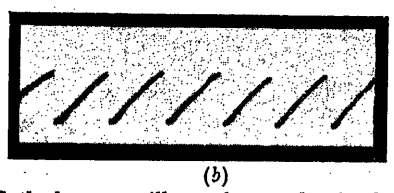
In many cases it is advantageous to repeat the linear time-traverse indefinitely. This can be achieved in a number of ways, of which the following are now best known.

Rotating Potentiometer.—This device can be used, like the inductance in $(ii)_1$ above, as a means of producing a linear current variation in the deflecting electromagnet or a linear voltage variation across the electrostatic deflecting plates. In its simplest form the rotating potentiometer consists of a motor-driven rheostat (a single turn of

high-resistance wire mounted on the edge of a disc) which gives a linear variation of resistance with time between the limits R and zero. A discontinuity occurs when the brushes on the rheostat reach the end of the wire, the resistance rising from zero to R linearly and suddenly dropping from R to zero. The cathode-ray spot consequently crosses the plate or screen at a uniform speed from left to right, when it suddenly jumps back to its zero position and the cycle of operations is repeated. The frequency of repetition is of course determined by the speed of revolution of the disc. When the potentiometer is used as a current-varying device in the electromagnet deflecting circuit it is important that the brush resistance should always be small, otherwise the current will vary erratically and the time deflection of the spot will be non-linear. Such a trouble is not likely to arise in the case of electrostatic deflection. In this case, however, there is a limited range of practicable voltage



(*a*)



(*b*)

FIG. 5.—Cathode-ray oscillograph records of voltage fluctuations in neon-lamp flashing circuit.

(*a*) Commencement of flashing.
(*b*) Steady oscillation.

variation consistent with sufficient mechanical strength and electrical resistance in the potentiometer wire.

The rotating-potentiometer method is limited to low speeds of traverse since it becomes impracticable, or at any rate very difficult, to obtain satisfactory working at high speeds. For recording low-frequency phenomena, however, it serves a very useful purpose.

The inductance and capacitance deflecting circuits shown in Fig. 4 may of course be used to give repeated linear traverses if the key shown in the diagram is replaced by a revolving commutator and brushes. The duration of make and break on the commutator will depend, of course, on the particular circumstances in which it is to be used.

Neon-Lamp Method.—The peculiar property of a neon lamp by virtue of which it requires a higher voltage to initiate than to maintain its luminosity has been utilized by a number of workers to produce an intermittent action of controllable frequency. This effect was first observed by H. St. G. Anson and S. O. Pearson,* using a condenser of capacitance C in series with a resistance R and a voltage E, the lamp being connected in parallel with the condenser. On making the circuit, the condenser begins to acquire a charge and the voltage v_c across its terminals will rise according to the law

$$v_c = E(1 - e^{-t/CR})$$

The lamp will flash as soon as the voltage across the condenser reaches the upper critical striking voltage. When this occurs the condenser becomes shunted by a fairly low resistance, the lamp, and consequently loses its charge. The lamp continues to glow until the condenser voltage v_c falls to the lower critical voltage at which current through the lamp ceases. The process is then repeated indefinitely. The time of a complete cycle is directly proportional to the capacitance in parallel and the resistance in series with the lamp. The periodic time is also affected by the applied voltage E. This device provides a very simple means of producing intermittent currents over a wide range of frequency. Cathode-ray oscillograph records of the voltage fluctuations across the condenser in such a circuit are shown in Fig. 5. The records show clearly the exponential rise

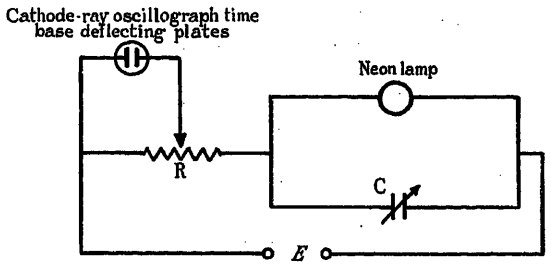


FIG. 6.—Neon-tube circuit for repeated linear time base.

of voltage as the condenser charges and the sudden fall as the lamp flashes. It will be seen that the voltage variation with time over the range lying between the two critical voltages of the lamp is approximately linear (actually, of course, the line forms a small part of an exponential curve).

N. V. Kipping* has made use of this property of the neon-lamp flashing circuit to give a repeated linear (or almost linear) deflection of the cathode rays in a low-voltage oscillograph. The circuit is shown in Fig. 6. The "time base" deflecting plates are connected as shown across a part of the series resistance R which limits the rate of charging of the condenser C. The frequency of repetition is controlled by varying R and C. With this arrangement Kipping was able to demonstrate the formation of a stationary pattern when the flashing frequency was synchronized with the wave-form under investigation. The method is advantageous when using an oscillograph in which it is not possible to photograph a single traverse of the cathode-ray "spot." It is useful also for the visual examination of single impulses or phenomena which occur at irregular intervals.

G. I. Finch, R. W. Sutton, and A. E. Tooke† have recently devised a modification of the neon-lamp time circuit by means of which cathode-ray oscillograph traces due to recurring electrical and magnetic phenomena

* See Reference (24).

* See Reference (25). † *Ibid.*, (26).

can be accurately superposed, even though the train-frequency be subject to wide and irregular fluctuations. The underlying principle of this time base lies in the use of a glowing neon lamp which is extinguished by energy furnished either directly or indirectly by the phenomenon under investigation. The circuit was developed primarily with a view to the study of ignition-coil phenomena, consisting of trains of damped oscillations recurring at somewhat irregular intervals. In spite of the irregularities in the contact breaker, the non-uniform cam surfaces and the variable speed of the cam drive, the oscillograms, each consisting of several thousand superposed traces, indicate that a remarkably good synchronization has been obtained.

The "Ticking-grid" Method.—A novel form of repeating the linear time-axis for cathode-ray oscillographs has been described by E. V. Appleton, R. A. Watson Watt, and J. F. Herd.* This involves a special triode oscillator the potential changes of which, applied to the deflecting plates, cause the cathode-ray spot to move uniformly from left to right over a suitable range in a definite and

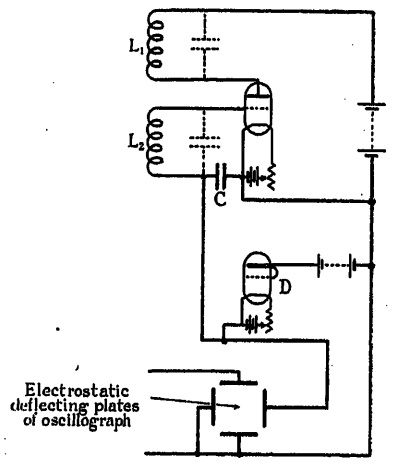


FIG. 7.—Linear time-base oscillator.

controllable time, returning to zero almost instantaneously. The circuit for supplying these voltages and applying them to the cathode-ray oscillograph is shown in Fig. 7. Oscillations of about 1 million per second are generated in the triode circuit which contains the coupled inductances L_1 and L_2 (flat spiral coils having sufficient self-capacitance to complete the oscillatory circuit). In the grid circuit of this oscillator a condenser C is connected in parallel with a diode D. With suitable adjustments, such an oscillator will generate very brief trains of oscillations with uniform periods of quiescence. During the short oscillatory period the grid side of the condenser C is rapidly charged negatively, so that the cathode-ray spot is caused to travel practically instantaneously from right to left, the negative grid potential reducing the anode current to a value at which oscillations can no longer be maintained. At this stage the condenser commences to discharge at a uniform rate through the saturated diode in a time determined by the constants of the diode and the capacitance of the condenser C. This causes the cathode-ray spot to travel uniformly from left to right during the quiescent period of the oscillator. The rise of grid potential then raises the anode current to a critical value sufficient to restart oscillation, when the whole process is repeated. To make the right-to-left journey of the spot very rapid, the natural frequency of the oscillator is kept high and the capacitance of the condenser C as low as possible (e.g. less than $0{\cdot}01\mu F$). The control of the rate of discharge of the condenser is most conveniently effected by means of the filament current of the diode. It is advisable, however, to run the valve filaments as brightly as possible to obtain the best conditions for linearity of the left-to-right deflection. Calibration of the time base may be effected by application of a sinusoidal oscillation of known frequency to the "vertical" deflecting plates of the oscillograph. If this a.c. frequency is 5 to 10 times the frequency of the time base, a check on the linearity of the deflection may be readily obtained.

This type of repeating linear time-base has been used by R. A. Watson Watt and his collaborators as a powerful means of studying the wave-form of atmospherics.

$(ii)_3$ *Circular or Elliptical Time Axis. Harmonic Comparison of Frequencies.*

The cathode-ray oscillograph provides a very convenient means of frequency comparison for high-frequency electrical oscillations. N. V. Kipping* and D. W. Dye† have both described such methods, and the latter has also applied them to the production of an approximately linear time-base for recording periodic phenomena.

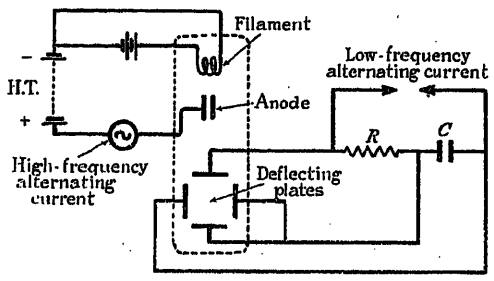


FIG. 8.—Low-frequency circular time trace with high frequency superposed on anode potential to give radial oscillation.

The simplest method of frequency comparison consists in forming a Lissajous figure by applying an alternating e.m.f. of known variable frequency to one pair of deflecting plates and the e.m.f. of unknown frequency to the other pair at right angles. When the ratio of these frequencies is a whole number the spot describes a Lissajous figure. If the ratio is an exact integer the figure is stationary, but if the ratio departs slightly from a whole number the figure appears to change slowly, repeating its original form at a frequency corresponding to the number of cycles per second departure from the exact whole-number ratio. The method can be applied conveniently up to a ratio of 10 : 1 in frequency; but much beyond this ratio the exact setting is somewhat troublesome. The method may be applied, however, to determine a high frequency (e.g. 10^6 cycles per sec.) in

* See Reference (27).

* See Reference (25).

† *Ibid.*, (28).

terms of an accurately known low frequency (10^3 cycles per sec.—a tuning-fork) in steps of, say, 10 : 1.

The alternative method, devised independently by Kipping and Dye, allows the direct comparison of greater frequency ratios than are possible by the Lissajous-figure method. The method consists in producing a circular or elliptical time-trace, of known frequency, on which the oscillations to be investigated are superposed. Kipping obtains the circular trace by the phase-splitting method indicated in Fig. 8, in which the resistance R is made equal to $1/(\omega C)$. In this way two equal deflections in quadrature produce the circular trace. The high-frequency oscillation is now superposed on the anode potential. This results in a small oscillation in the

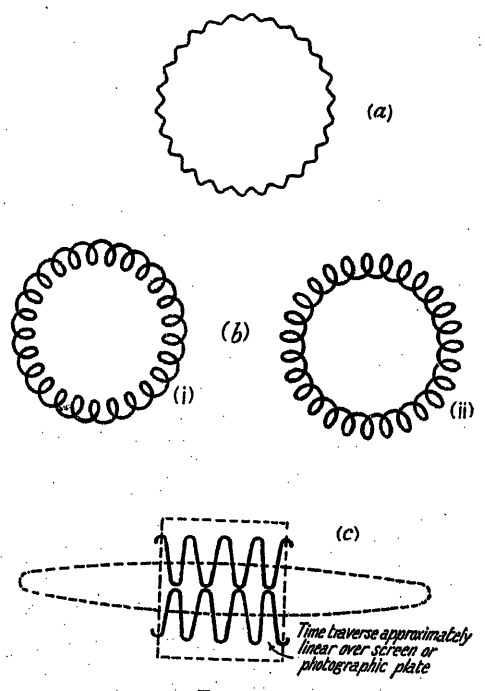


FIG. 9.

(*a*) Radial deflection of frequency 26 times that of circular time-base.
(*b*) Circular deflection of frequency 26 times that of circular time-base.
(i) Circular rotations in same direction.
(ii) Circular rotations in opposite directions.
(*c*) Linear oscillations superposed on long elliptical time-base.

velocity of the cathode rays and a consequent oscillation in the sensitivity of the oscillograph. The diameter of the circular trace therefore varies with the total instantaneous anode potential, the alternating voltage thus producing a radial displacement. If the frequency of the alternations applied to the anode circuit is any whole multiple N of the circle frequency, then the circle will have N waves on its circumference [see Fig. 9(*a*)]. A disadvantage of this method of superposition is that a rather high voltage at the upper frequency is required to produce a sufficient radial deflection.

Dye has used this method also, employing a tuning-fork of standard frequency (1 000 cycles per sec.) provided with an amplifier and "smoother" as a source of alternating current for the circular time-base. He describes also two other methods in which the high-frequency oscillation is superposed on the circular (or elliptical) time-base (*a*) as a small circular movement and (*b*) as a vibratory movement in a fixed direction. With regard to (*a*), the appearance is that of a circular looped pattern, the number of loops being $(N \pm 1)$, where N is the ratio (a whole number) of the superposed frequency to that of the circle. The plus and minus signs arise on account of the simultaneous rotation of the circular time-base and the high-frequency oscillation in the opposite or the same direction [see Fig. 9(*b*)].

This method is, however, unsuitable for the examination of wave-forms. For this purpose method (*b*) is preferable. The high-frequency motion now takes place along a straight line of fixed direction, whilst the low-frequency time-base remains as before. Instead of using a circular time-base, however, the spot is now arranged to follow an elliptical path of large eccentricity. This is achieved by reducing the potential applied to one pair of plates and increasing the potential of the component in quadrature. The time base is now a long, narrow ellipse with the high-frequency displacement at right angles to the major axis [see Fig. 9(*c*)]. By this means a considerable portion of the "time-ellipse" is now described with almost uniform velocity, thus providing an almost linear time-base. The wave-form of a superposed high-frequency oscillation is delineated in this region without appreciable distortion. These three methods developed by Dye are very convenient for the study of the frequency and wave-form of high-frequency oscillations by means of a simple visual-type oscillograph (e.g. the Western Electric 300-volt oscillograph). When the stationary figure has been obtained it is possible to obtain a record directly on bromide paper by placing it in close contact with the phosphorescent screen for a few seconds.

(*B*) *Potential Dividers.*

When the voltage applied to the electrostatic deflecting plates of the oscillograph becomes so high that the maximum possible deflection is attained, it is necessary either (*a*) to reduce the sensitivity of the oscillograph by increasing the distance apart of the plates and/or reducing their length, or (*b*) to provide some means of reducing in a known ratio the potential applied to the deflecting plates of the oscillograph.

With regard to the second method, it is important to ensure that this potential-division is not accompanied by distortion of wave-form. This implies that the distribution of current and voltage is not appreciably disturbed by the introduction of the potential divider, as might occur by the introduction of appreciable resistances or capacitances in a resonant circuit. At very high frequencies or in the case of impulses of very short duration, such a condition is not always easy to fulfil. It is clearly impossible to deal even briefly with all the cases which may arise, but it may be of some value to refer to one or two specific cases of general interest. The question of potential-dividers for cathode-ray oscillographs has been dealt with in some detail by W. Rogowski, O. Wolff, and H. Klemperer.* They refer to cases where potentials of the order of 10 to 30 kV have been applied *directly* to the deflecting plates of a high-voltage oscillograph (the exciting potential

* See Reference (29).

being of the order of 60 or 70 kV). In general, however, they regard 5 kV as an average upper safe limit of voltage to apply to the deflecting plates of such an oscillograph. High voltages require exceptionally good vacuum conditions and large clearances between the leads to the deflecting plates and the body of the oscillograph, otherwise a discharge is likely to occur across the internal insulation.

Potential division is most conveniently carried out by means of resistances or condensers or combinations of both.

(*a*) *Capacitance Potential Dividers.*

A simple arrangement which is often used is indicated in Fig. 10(*a*). Two condensers, C_1 and C_2, are connected

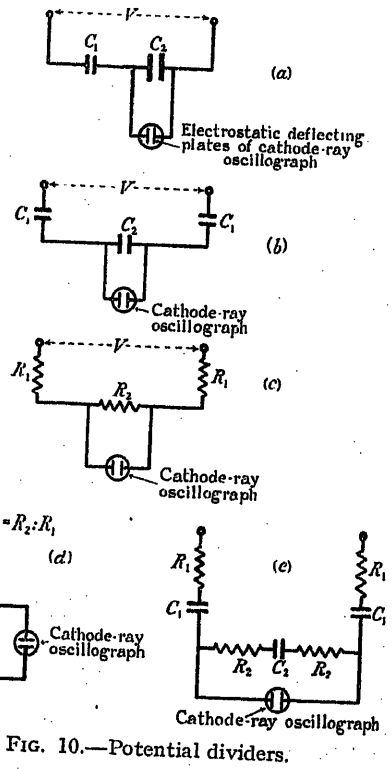


FIG. 10.—Potential dividers.

in series across the points in the main circuit where the potential fluctuation is to be recorded. As mentioned above, these condensers must be chosen so as to interfere as little as possible with the distribution of voltage and current in the main circuit. If V is the instantaneous potential applied to the divider and v that across the condenser of capacitance C_2, and consequently across the oscillograph deflecting plates, then

$$\frac{v}{V} = \frac{C_1}{C_1 + C_2}$$

or, in the case where C_2 is large compared with C_1,

$$v/V = C_1/C_2.$$

It is preferable in all cases that the total capacitances C_1 and C_2 should be kept as small as possible. The capacitance C of the oscillograph deflecting plates and leads can often be neglected, but in cases where C_1 and C_2 are very small, e.g. when recording very high-frequency oscillations or impulses of short duration, due allowance must be made for the small capacitance C (usually of the order of a few centimetres only) in parallel with C_2. Although the circuit shown in Fig. 10(*a*) serves the purpose at relatively low frequencies it is preferable to divide the condenser C_1 into two equal parts so as to render the arrangement symmetrical as shown in Fig. 10(*b*). The relations connecting the voltage-ratio and the capacitances then become (neglecting the capacitance of the oscillograph)

$$\frac{v}{V} = \frac{C_1}{C_1 + 2C_2}.$$

or, when C_2 is large compared with C_1,

$$v/V = C_1/(2C_2)$$

At very high frequencies it is, of course, equally important to make allowance for capacitance to earth—particularly in the case of oscillographs in which the deflecting plates are surrounded by an earthed metal enclosure.

It should be noted, however, that the above considerations would require modification in the case of "gas-filled" oscillographs of the Western Electric and von Ardenne types. A correction is then required for the effective internal resistance of the oscillograph. The simple potentiometer formulæ are only applicable to high-vacuum oscillographs.

With the arrangement shown in Fig. 10(*b*), in which C_1 and C_2 are both 50 cm, W. Rogowski has obtained with a high-voltage oscillograph correct potential-division and exact reproduction of wave-form for complex impulses (including square-topped waves) of duration 10^{-6} sec.

The oscillograph may, of course, be used equally well for recording the *current* fluctuations in a circuit if the deflecting plates are connected directly or via the potential divider across a known non-reactive resistance in series with the main circuit. The permissible values of this resistance will of course depend on the particular conditions obtaining in the main circuit.

(*b*) *Resistance and Combined Resistance-Capacitance Potential Dividers.*

The condenser type of potential divider is particularly suitable when the phenomena to be recorded are of very short duration. For slowly-varying effects the method is not so useful, the leakage of the condensers beginning to be noticeable. An alternative is that of the simple high-resistance potential divider shown in Fig. 10(*c*), in which

$$\frac{v}{V} = \frac{R_2}{2R_1 + R_2}$$

the resistances being, of course, non-reactive. The resistance potentiometer must be used with caution, otherwise it is liable to produce serious distortion of wave-form. For example, the resistance method would be quite unsuited to the case of recording variations in a small electrostatic charge such as that produced by pressure in a piezo-electric crystal of small capacitance.

Rogowski has also experimented with various combinations of resistance and capacitance potential divider such as those shown in Figs. 10(*d*) and 10(*e*) as a means of subdividing voltage conditions intermediate between those of (*a*) and (*b*). He shows that potential dividers of the resistance and resistance-capacitance types are not suitable for dealing with phenomena of very short duration, in consequence of the capacitance of the deflecting plates of the oscillograph. For such purposes only the capacitance type of potential divider can be used with safety.

(*C*) *Timing of Single Impulses.*

The recording of an alternating voltage by means of a cathode-ray oscillograph is a relatively simple matter. The spot is set in oscillation, under the action of one pair of deflecting plates, before the traverse occurs, and it continues to oscillate both during and after the traverse of the spot across the plate. In the case of a single impulse, however, it is necessary (*a*) to traverse the spot at such a speed that the resultant record shows sufficient detail, and (*b*) to arrange that the complete electrical impulse occurs whilst the spot is on the photographic plate. The simultaneous achievement of these two conditions often requires considerable ingenuity and technical skill.

Take, for example, a relatively simple case of an impulse lasting 0·001 sec., a recording speed of 20 or 30 metres per sec., and a plate length of about 5 cm. Using the single-traverse inductance method described on page 8, we require to arrange that the impulse deflection commences about 1 cm from the left-hand edge of the plate, the spot being deflected initially to a point off the left-hand edge of the plate by means of an auxiliary winding on the electromagnet. A time-delay mechanism is necessary and for this purpose a double-switch is convenient. This switch, which may be operated electrically or mechanically, is arranged to close first the deflecting circuit (through the electromagnet or the condenser) and at a definite instant later to initiate the electrical impulse. In the particular case we are considering the time interval will be of the order of 0·001 sec. A simple arrangement* consists of a pivoted gravity-arm carrying a pair of contact rods of adjustable length, which fall into mercury cups. The arm is prevented from rebounding after the contacts enter the mercury by means of a spring clip. Assuming the velocity of entry of the contact rods into the mercury to be about 2 metres per sec., then 2 mm difference of setting in the contacts corresponds to a time interval of 0·001 sec. This simple arrangement has given good results in recording impulses of total duration of the order of 0·0001 sec., e.g. the damped oscillation of a condenser discharging through an inductive resistance at a frequency of 20 000.

The same principle is, of course, applicable to much higher speeds of recording. The gravity control of the contacts must in such cases be replaced by a strong spring, and the weight of the arm carrying the contacts must be reduced as much as possible. The contact arm in this case may be operated electromagnetically. The delay between the commencement of the traverse of the spot and the instant of application of the impulse to be recorded is in this case conveniently adjusted either by varying the contact-gaps by a fine screw or by varying the tension in the control spring.

An alternative to this arrangement employs a revolving commutator with two pairs of adjustable brushes to give the required time-interval. This device can be used at very high speeds, but it is then liable to give trouble due to uncertain contact between brush and commutator.

Since the advent of the Dufour high-voltage oscillograph, a considerable amount of attention has been paid by high-voltage electrical engineers to the study of the effects of lightning and of surges due to switching in high-voltage lines. In the latter case the "timing" of the record can be brought under control by a suitable arrangement of automatic switches. For example, K. B. McEachron* describes a study of the time-lags in spark-gaps by means of the Dufour oscillograph. The time-base of the record was that used by Dufour† in

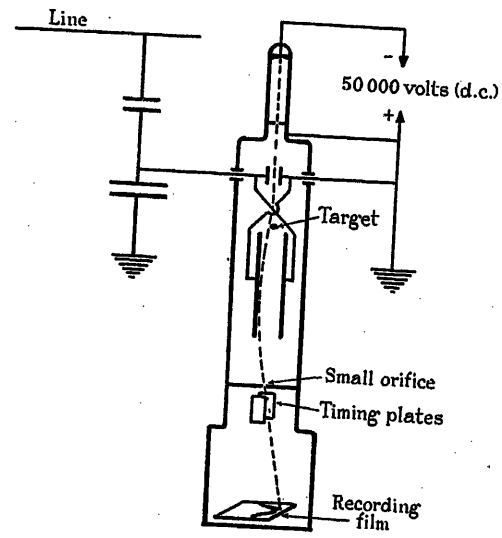


FIG. 11.—Norinder relay-oscillograph.

which a relatively low-frequency oscillation is impressed on the cathode rays in a direction at right angles to the direction of rotation of the recording drum (supporting the film). The high-voltage impulse was then arranged to deflect the rays at right angles to the low-frequency deflection, the timing of the impulse being carried out by means of an automatic switch in a manner somewhat similar to that described above. K. Berger‡ has studied by such methods the surges arising from short-circuits, earth faults, and switching operations in high-voltage lines. By means of the oscillograph he followed the progress of a surge through a transformer winding. As a result of such observations he was able to point out the dangers of using certain forms of choking coils for protection against surges.

The recording of lightning effects is a much more difficult matter, on account of the uncertainty in the time of arrival of the impulse. The timing in this case must necessarily be automatic, the lightning impulse itself initiating the time deflection of the cathode-ray

* Devised by Mr. E. H. Lakey, B.Sc. Associate Member.

* See Reference (30). † *Ibid.*, (12). ‡ *Ibid.*, (31).

"spot." An ingenious arrangement for such a purpose has been devised by H. Norinder.* The arrangement employs a beam of cathode rays to perform the dual function of relay and oscillograph (see Fig. 11). The cathode stream is initially stopped by a small target. When a lightning surge arrives a proportionate deflecting potential is applied to the upper pair of deflecting plates and the beam moves off the target. Below the target the beam is bent back again by the same potential reversed by a second pair of deflecting plates. By suitable adjustment of the dimensions and spacing of these two pairs of deflecting plates the beam is caused to pass through a small orifice *whatever the value of the applied potential.* This orifice may therefore be regarded as the "pivoting point" of the cathode stream. A third pair of deflecting plates mounted below serve to provide the necessary "time-deflection." It will be seen that the cathode rays fall on the plate only during the passage of the impulse. The relay function is performed by the oscillograph itself, and a complete record is made of any transient whenever it may occur. This device has been used extensively in the study of lightning and spark discharges and of surge waves. It is suitable for the registration of random potential and current variations of whatever nature.

W. Rogowski, O. Wolff, and H. Schäffer† have also devised relay systems by means of which the passage of the surge wave is made to expose the photographic film. By a suitable choice of circuit constants the delay in putting the oscillograph into operation could be reduced to an interval of the order of 3×10^{-9} sec., during which time the surge has travelled only 1 metre.

In conclusion the author desires to express his indebtedness to the Admiralty for permission to publish this paper.

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[The discussion on this paper will be found on page 70.]

ACCURACY OF MEASUREMENTS MADE WITH HOT-FILAMENT CATHODE-RAY TUBES OF THE GAS-FOCUSED TYPE.

By Professor J. T. MacGregor-Morris, Member, and H. Wright, B.Sc.(Eng.), Graduate.

(*Paper first received 8th April, 1931, and in final form 6th January, 1932; read before the* Meter and Instrument Section *5th February, 1932.*)

Summary.

The rapid development of the hot-filament type of cathode-ray tube is outlined, and various sources of error which are encountered in its use as a measuring instrument are discussed, including errors inherent to the tube, especially those due to the effect of gas conduction, then errors of manipulation and those due to external influences are reviewed.

Recording is next dealt with, including photographic methods, and various methods of calibrating are considered. The chief part of the paper, however, deals with what is known as the "threshold effect," a quantitative examination of which is given, together with graphs showing its relation to the various variables, such as frequency and the effect of resistance in series with the deflecting plates.

Suggestions are put forward as to the cause of the threshold effect, and the paper concludes with recommendations for accurate working.

In an Appendix particulars relating to the latest pattern of low-voltage tube are given, and its sensitivity is discussed.

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Appendix.—Particulars relating to later pattern of tube. Typical voltage/deflection graphs. Sensitivity.

Introduction.

The rapid development of the hot-cathode tube as an instrument for measuring electrical quantities is an interesting example of the assistance that pure physics is constantly giving to electrical engineering, and also of the fact that, unless the principles underlying the operation of the apparatus are clearly understood, erroneous conclusions may be drawn from the records obtained.

The Wehnelt cathode invented in 1905 was soon introduced into English and German types of cathode-ray tubes, and later was incorporated in the Western Electric type. Recently, it has been embodied in the von Ardenne tube (introduced in 1929) which, though quicker in recording, requires an intermediate third voltage of between 100 and 300 volts.

On account of the rapidly extending use of such tubes it appeared desirable to collect together the various methods used for recording results, and then to give a detailed examination of the causes of error, with a view to improving the precision obtainable and to increasing the speed of recording.

Many sources of error, for example those due to lack of perfection in manufacture and to external fields, are obvious. This paper, however, deals chiefly with the more obscure causes of such errors, e.g. the "threshold effect."

It should be noted that the word "error" is used rather as meaning a departure from simple theory than in the usually accepted sense. Obviously if a tube is calibrated all the "errors" are accounted for, except when the conditions of use change, when naturally a new calibration would be necessary. In the main, therefore, "error" here refers to the departure of the sensitivity of the tube from the theoretical sensitivity, this departure, of course, including any non-linearity in the relation between voltage and deflection.

General Errors in Measurements.

Inherent to Tube.

Non-parallel plates.—The tubes now available seldom have serious faults due to defects in manufacture, and in consequence the likelihood of obtaining a tube with deflecting plates which are not parallel is small, although plates may distort after some time has elapsed. The errors associated with this fault in construction are only apparent when deflections are being made in two direc-

tions mutually at right angles, i.e. when both pairs of plates are in use.

In Fig. 1, if the beam has already had a displacement along the line AB the displacement produced by the pair of plates under consideration would be different when in the position A than when in the position B. If x is the displacement of the cathode stream from the

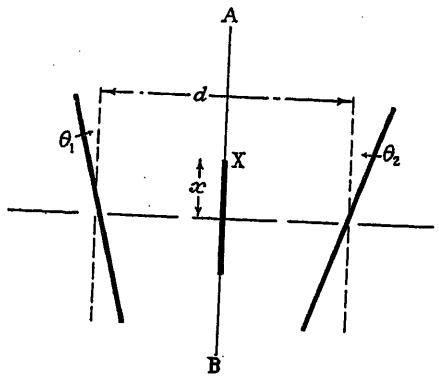


FIG. 1.

centre, and a voltage V is applied between the plates the potential gradient at X will be

$$\frac{V}{d + x(\tan\theta_1 + \tan\theta_2)}$$

The potential gradient if there were no distortion of the plates would be V/d.

Hence the error is

$$\frac{\frac{V}{d} - \frac{V}{d + x(\tan\theta_1 + \tan\theta_2)}}{V/d} \times 100 \text{ per cent}$$

$$= 1 - \frac{d}{d + x(\tan\theta_1 + \tan\theta_2)} \times 100 \text{ per cent}$$

If the deflection in the direction AB were varying sinusoidally, the difference between the deflection at right angles to AB, and at the extremes of the motion in the direction AB, would be twice this amount.

In the case of the Standard Telephone Co.'s tube:*

$d = 0{\cdot}5$ cm; $b = 2$ cm; and assume $x = 0{\cdot}2$ cm, and $\tan\theta_1 + \tan\theta_2 = 0{\cdot}1$ ($\theta_1 = \theta_2 = 3°$), then error between two extremes

$$= 2\left(1 - \frac{0{\cdot}5}{0{\cdot}5 + 0{\cdot}2 \times 0{\cdot}1}\right) \times 100 \text{ per cent}$$

$$= 2(1 - 0{\cdot}962) \times 100 \text{ per cent} = 7{\cdot}6 \text{ per cent}$$

Error of Curvature of Screen.—When the radius of curvature of the fluorescent screen is not equal to the distance between the deflecting plates and the screen or the centre of curvature is not at the deflecting plates, an error up to a few per cent may occur at large deflections, and reference should be made to the manufacturer's handbook.

The Effect of Gas Conduction between Deflecting Plates.—Owing to the fact that the gas in the tube is ionized when the cathode beam is in action, there is a conducting path between the plates. The effect of this is only apparent under two sets of conditions: (1) When the amount of energy for producing a deflection is extremely small; and (2) When a resistance is placed in series with one of the deflecting plates, in which case the error is always present, no matter what amount of energy is available.

In the first case, if the resistance is R, and the deflecting voltage V, the power loss in the gas is V^2/R watts. If the source of energy is a charged condenser of very small capacitance, as soon as the condenser is connected to the plates the voltage will decrease exponentially and no true deflection will be recorded. Another effect apparent in such a case would be due to the capacitance between the plates if the tube is being used on radio-frequency voltages.

If R is the resistance between the plates, and R_1 is the resistance in series with one of the plates, the actual voltage across the plates will be $RV/(R + R_1)$, where V is the deflecting potential.

The error is therefore

$$\frac{V\left(1 - \frac{R}{R + R_1}\right)}{V} \times 100 \text{ per cent}$$

and if $R = kR_1$ the error is

$$\frac{R_1}{R_1(k + 1)} \times 100 \text{ per cent}$$

$$= \frac{1}{k + 1} \times 100 \text{ per cent}$$

As R is not constant, but varies with the deflecting voltage, this matter is dealt with more fully under the Section entitled "The Threshold Effect."

ERRORS OF MANIPULATION.

The Effect of Resistance in the Anode Circuit.

The makers of hot-cathode tubes recommend the use of a resistance between the anode and the positive of the high-tension supply, so as to limit the emission in the event of over-voltage on the anode, or over-heating of the filament, or in the much more remote case of the formation of an arc between the anode and the filament. As the emission current is carried by this resistance a drop in voltage occurs, so that the anode does not receive the voltage of the source of supply. The effect of this difference in increasing the sensitivity of the tube is not mentioned in the makers' instructions, and in the case of the No. 4224 tube the following figures are typical:—

Nominal anode voltage	= 200 volts
Series resistance	= 2 000 ohms
Emission current	= 0·5 milliamp.
Error for electrostatic deflections	= ½ per cent
,, ,, electromagnetic ,,	= ¼ per cent

The importance of not exceeding this value of limiting resistance will therefore be seen.

* In the remainder of the paper this tube will be designated as the No. 4224 tube, and in the Appendix the later pattern tube will similarly be referred to as the No. 4018A tube.

Threshold Effect.

This effect was described by Captain P. P. Eckersley,* who stated that a certain " threshold " value of deflecting voltage had to be reached before any deflection took place. The result of the present investigation goes to show that this is only approximately true, as the sensitivity although lower is not zero, for very small deflecting voltages. For electromagnetic deflections, however, no such effect is apparent. This subject is dealt with more fully in the latter part of the paper.

Error due to Non-central Zero Spot.

This error only appears when the zero spot is near the edge of the screen, and then the curvature error comes into evidence in what are really small deflections. The curvature correction would have to be applied to the zero position as well as to the deflected position.

The Use of External Deflecting Plates.

The use of a pair of metal plates fixed outside the tube in order to obtain deflections by applying a voltage to the plates has been suggested. With a cold-cathode, high-vacuum tube, results with this may be possible, but with the type under consideration deflections are not possible. This is because of the comparatively large quantity of gas in the tube, which, when the tube is in operation becomes highly ionized by electronic collision of the electrons from the cathode stream and the gas molecules in the tube. By placing plates outside the tube and applying a difference of potential to them, the ions in the tube segregate under the influence of the electric field thus set up, and charges collect on the walls of the tube, largely reducing the potential gradient across it and so producing very little deflection of the spot.

As a result of work done by H. Whitaker at East London College on the use of external deflecting plates, if was found that for a cold-cathode tube the ratio of deflections using internal and external deflecting plates was about 111:1. The value found for the 4224 tube was 117:1. From a formula given by A. G. Webster† relating to the screening effect due to the high permittivity of glass, the field strength inside an infinitely long tube having $\frac{1}{16}$-in. walls and $\frac{5}{8}$-in. external diameter is 0·72 of the field outside, and for a tube $1\frac{5}{8}$-in. external diameter and walls of the same thickness, it is 0·92, assuming that the tube is placed between parallel plates of infinite extent. Hence it seems that only static charges will account for the greatly reduced deflection for potentials applied to external plates.

Non-uniform Field of Coils.

No actual measurements have been made of the field distribution in the space between the coils. There is, however, nothing to point to any non-uniformity of the field over the small area enclosed by the extreme positions of the beam.

* "The Design and Distribution of Wireless Broadcasting Stations for a National Service," *Journal I.E.E.*, 1923, vol. 60, p. 513. Also see remarks by Mr. Watson Watt and Mr. MacPherson in the discussion, and the author's reply.

† "Theory of Electricity and Magnetism" (Macmillan & Co., 1897, p. 378).

EXTERNAL INFLUENCES.

The Influence of Stray Magnetic Fields.

It is customary to bring the spot to a convenient part of the screen by means of one or two horseshoe or bar magnets. This is usually done by arranging a magnet situated at the end of the tube beyond the screen. It is generally necessary to have the magnet fairly close to the tube in order that it may have sufficient effect. The necessary corollary to this is that at least the end of the beam must be in a widely diverging magnetic field, so that as the beam is deflected

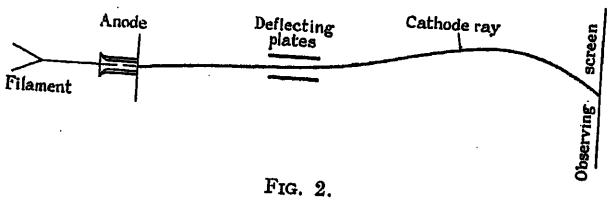


FIG. 2.

it is moving across this non-uniform field, which produces a force which will either add to or subtract from the applied deflecting force. The error which would be produced by this is under certain conditions very great. When the tube supplied by Messrs. Edwards is considered, another magnet has to be introduced. Owing to the heavy filament current used, it is seldom that the cathode stream from the lime spot on it goes through the hole in the anode. In this case a magnet has to be used to cause the stream to enter the hole, and when it

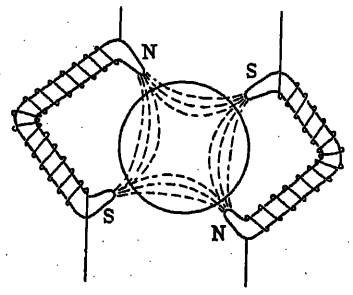


FIG. 3 (diagrammatic).

emerges it is usually found that the spreading field from the magnet causes the stream to strike the wall of the tube at some point along it. This necessitates the introduction of the magnet considered above, and this causes the beam to take the form shown in Fig. 2. Owing to the beam impinging on the screen at an angle, it is scarcely possible to obtain a small spot, and the deflection is unlikely to be proportional to the deflecting force. Several methods were tried by the authors and the most successful was the following.

A pair of small electromagnets were made as shown in Fig. 3 with $\frac{3}{16}$-in. iron rod flattened out at the ends and bent at right angles. These were mounted on a piece of paxolin sawn across the middle, having a hole in the centre to fit closely around the tube, the two halves being held together by screws. When the two windings were connected in series with two variable resistors and

supplied from a 2-volt cell, it was found easy to control the cathode stream and make it enter the hole by varying the resistances and rotating the paxolin carrier around the tube.

The stray field from this arrangement is relatively weak, and by reversing the direction of the current through the coils, either in one or both, it is only necessary that the mounting should be able to rotate through 90°. It was found that after the current had flowed through the coils there was sufficient remanent magnetism in the iron (which had not been annealed after flattening and bending) to do away with the battery. It has been used in this way for about a year without a battery.

The position of the tube with respect to any stray magnetic fields, e.g. from instruments or the earth's field, must obviously remain unaltered during calibration and use.

External Electric Fields.

It is unlikely that the tube would be subjected to any strong electric field, and in case of doubt it would be a simple matter to surround the tube with a suitable earthed metallic cage or screen.

If deflecting coils are used at a potential differing greatly from that of the anode, there is a possibility of electrostatic action occurring, so that the preferable way of using the coils is to connect them to the anode, but if this cannot be done a layer of tinfoil round the tube under the coils is sufficient to act as a screen when connected to the anode. Although it is difficult to produce a deflection by a potential applied outside the tube when a steady voltage is used, it is possible to get a movement of the spot when the voltage is alternating.

Recording.

Tracing.

The simplest method of obtaining a true record of any paths traced out by the spot is to use tracing paper and make a tracing of the curve obtained. There are two objections to this, one being that in the case of a tube like that supplied by Messrs. Edwards, where the fluorescent screen is not on the end of the tube, but on a separate mounting, it is impossible to trace it accurately. The other objection is that where the phenomenon is not repeating with regularity it is extremely difficult to reproduce the mean curve. The first difficulty can be overcome by using a camera with a focusing screen, and tracing the image produced on it. This is not possible where the speed of travel of the spot is too great to produce a very intense line on the fluorescent screen. A further difficulty is that it is necessary to have complete darkness in order to be able to see the trace on the camera screen.

By Direct Photography.

By Film or Gaslight Paper.—An alternative to tracing by hand is to do it automatically by laying a photographic film on the end of the tube and developing the latent image. Gaslight or bromide paper can be used in place of the film. It is difficult to state definitely which of the two, film or paper, is the better, as the conditions cannot be specified. It is, however, much easier to form a damp piece of gaslight or bromide paper to the end of the tube than to adapt for this purpose the comparatively unyielding film. On the other hand, the film is far more rapid photographically than the paper. The H. & D. numbers for the film and paper would be about 300 and 20, or relatively 15 to 1. The film, even if panchromatic, is more sensitive to blue or green light than to yellow, and the opposite is the case with the paper. This will make the relative speeds still more unequal. Any number of copies can be printed from the film, while it would only be possible to do this with the paper after a considerable amount of trouble.

By Plaster Cast.—This method, although interesting, is difficult to realize in practice. A photographic emulsion is made and run on the surface of a plaster of paris mould of the end of the tube. When the emulsion has set, the mould is used in the same way as the film, development being carried out by pouring the fluid into the cup of the mould. The trouble entailed by this method renders it unsuitable for obtaining a large number of records. The fact that the emulsion with the image is stuck to the cast renders the method cumbersome, and it is not known whether stripping solutions would remove it in order to transfer it to a glass plate. The possibility of using a pantograph has been suggested.

Camera Photography.

The simplest way of recording is by means of the camera. A darkened room is not necessary in this case, as the tube and the camera can be fitted into a small light-tight box, the camera shutter being operated from outside. The one great objection to this method is that only a small fraction of the photographic energy of the trace on the screen is available for producing an image on the plate, therefore making a long exposure a necessity.

Typical Results.—Using a camera with an aperture of F/7·7, and obtaining an image reduced about two-thirds, and an ordinary plate with a speed of 1 400 H. & D. with the Edwards tube, which has a mica screen, the exposure necessary for a mean speed of travel of the spot of 3 metres per sec. is about 40 seconds when the tube exciting voltage is 350 volts.

With a tube having the fluorescent material mounted on a mica screen, only about $\frac{1}{2}$ per cent of the total light energy is received on the sensitized emulsion, while with the glass mounting the value is about 4 per cent, this figure having been calculated and confirmed experimentally. It should, however, be mentioned that the direct-contact print does not yield a sharp record, owing to the thickness of the end wall of the tube being interposed between the luminous spot and the film.

Methods of Calibration and Evaluation.

General Remarks.

If the connection between the deflecting force and the deflection were of a strictly linear nature, it would be a simple matter to evaluate the traces, as all that would be necessary would be to obtain two points to establish the constants of the law. Unfortunately it is not so simple, and practically the only way of evaluating the results is to resort to preliminary calibration.

The authors found that the best way of measuring-up

records was by means of a co-ordinatograph, but dividers and scale are more simple to use, though not so accurate. In the case of a truly linear calibration a pantograph could be used for enlarging from the photographic image to a curve on squared paper. Once a calibration curve is obtained connecting the co-ordinates of a point and the quantity to which it relates, it is a straightforward matter to apply the calibration. Several methods of calibration follow, and in addition a brief description of a method which does away with preliminary calibration.

Methods of Obtaining a Calibration Record.

Using Direct Current or Voltage.—One method is to produce a deflection of the spot by a known value of voltage on the deflecting plates, or a known current through the coils, and record the position of the spot by one of the methods described previously.

Should it be desired to check the value of the deflection produced by a given force as the beam is moved transversely to the direction of deflection, all that is necessary

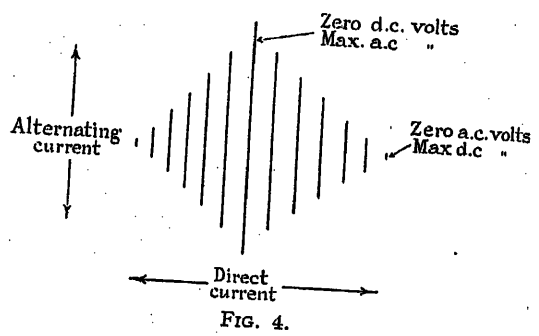


FIG. 4.

is to apply a steady deflecting force in the transverse direction and repeat the process.

Using Alternating Current or Voltage.—No advantage is obtained by the use of this method, which uses the peak of an alternating wave, while it has several disadvantages. Either the quantity must be sinusoidal or its peak value must be known, two conditions which it is sometimes difficult to fulfil, and the time for tracing, photographically or otherwise, is longer than it is for the spot. It is scarcely possible to use the relation between the sinusoidally varying quantity and time to obtain the relation between force and deflection, as it is seldom that the time base of such an arrangement can be calibrated in terms of time.

Calibrating in Two Mutually Perpendicular Directions.—Where it is desirable to calibrate along two axes at right angles simultaneously, it can be done if a sinusoidal alternating quantity is available. If direct current is applied in one direction and alternating current applied to produce deflections at right angles to this, the resultant record would be a series of spaced straight lines, and as the alternating part is varied as well as the steady part a diagram is obtained which would resemble Fig. 4.

If there is doubt as to whether a given relationship between force and deflection holds over all parts of the screen, the above method can be so modified that a constant alternating quantity is applied in one direction and a steady quantity varied in the other direction, these two being finally interchanged and the process repeated. In this case a grille pattern is obtained, either with all the lines parallel or some diverging, depending on the constancy of the force/deflection relation (see Fig. 5).

By doing this and then superposing any other trace required, the whole becomes, by the insertion of a few numbers corresponding to the value of the cross lines, a complete graph. It should be mentioned that this is not easy photographically, because the ends of the lines are distinctly brighter than the middles, and, owing to stray parts of the beam in the tube producing a halo round the spot, fogging of the negative occurs.

Simultaneous Calibration and Recording.—An interesting method due to R. M. Wilmotte* evaluates any point on a stationary trace on the screen directly. By means of two rotating commutators, one for each pair of plates, the voltages under analysis and a d.c. voltage are applied alternately to the two pairs of plates, the commutators being so proportioned that for a large part of a revolution the voltage under analysis is applied, the direct current being applied for the remaining part. By varying separately the values of the d.c. voltages the spot produced by them can be made to move over the screen until it is coincident with the trace, so that the co-

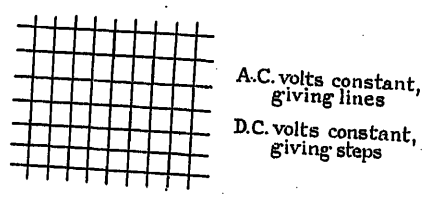


FIG. 5.

ordinates of any point of the trace can be measured in volts. By this means the necessity of preliminary calibration is dispensed with, but on the other hand it is only suitable for use where the trace under analysis is repeating exactly for as long as it takes to evaluate in this way. This method has been tried out by Mr. C. A. Luxford at East London College, and has been found to work excellently.

THE THRESHOLD EFFECT.

In the paper by Captain P. P. Eckersley quoted previously, a common use of the cathode-ray tube for radio-frequency measurements is described, and a statement to the effect that the tube appears to be insensitive to low values of deflecting voltage is made, and that voltages less than 8 to 12 volts apparently produce no deflection. This voltage was called by Capt. Eckersley the "threshold voltage." It was also stated that the effect would be diminished by reducing the filament current or the anode voltage.

The existence of this effect was proved by the present authors in the case of a simple form of tube of German manufacture, and it was found that the tube, though less sensitive to voltages below about 10 volts than it was to voltages above this figure, still gave measurable deflections.

* *Journal of the Franklin Institute*, 1930, vol. 209, p. 809.

Introductory Remarks on the Experiments Made.

A photographic method of recording was decided upon and a No. 4224 tube was housed in a black box in which was also a camera, so that all the work could be done in an undarkened room. It has previously been found in the course of some other work that the relation between deflection and current when coils were used for producing deflections was linear. Use was therefore made of this fact for producing a reference base for the electrostatic deflections. A pair of coils were fixed to the tube so that they would produce deflections in a horizontal direction, while a pair of plates were used for producing vertical deflections.

Experimental Evidence of the Existence of the "Threshold Effect."

A number of photographic records were first made with a view to determining whether the threshold effect was one of geometry, in that the effect may be due to the position of the beam in the tube, any stray effects being possibly due to charges on the tube walls. The records were made in the form of (*a*) spaced dots, these being produced by a series of steady deflecting potentials; (*b*) spaced parallel lines; and (*c*) a grille pattern. The values obtained from this last record are given in Table 1.

TABLE 1.

Voltage	Deflection, mm	
	P_x plates	P_y plates
+ 7·8	6·34	6·49
+ 5·2	3·74	4·32
+ 2·6	1·72	2·05
0	0	0
− 2·6	− 1·67	− 1·83
− 5·2	− 3·99	− 4·10
− 7·8	− 6·63	− 6·52

The fact that the lines neither converge nor diverge at the ends shows that the position of the beam in the tube does not influence, to a measurable extent, the deflection produced by a given voltage. This was further confirmed as follows. The beam was deflected simultaneously by two forces at right angles, one electrostatic and the other electromagnetic, and a diagonal trace with a kink at zero was obtained. A biasing voltage was then applied in series with the alternating current in two opposite directions successively, the three traces being recorded on one negative, and the kink was found to move along the axis of zero voltage. If the threshold effect happened only in the zero position of the beam, the kink would move at right angles to the line of voltage deflection.

The Development of the Equation connecting Voltage and Deflection.

The equation which was found to connect the deflection and voltage was of the form

$$\delta = KV - k\sqrt{[\pm (i - i_0)]}$$

where δ = deflection in millimetres,
V = deflecting potential,
i = conduction current at the voltage V,
i_0 = ,, ,, ,, zero voltage,
K = sensitivity constant as derived theoretically,
k = constant.

The alternative sign under the root is explained by the fact that the space charge must disappear at one plate and appear at the other as the voltage on the deflecting plates changes sign, so that by this means a simple way of taking account of the relative nature of the potential on the deflecting plates is obtained.

Four examples of experimental curves are given in Fig. 6 with the corresponding conduction currents in Fig. 7, for anode voltages of 350, 320, 280, and 250 volts, and in addition Fig. 6 shows points obtained from the equation above. The results obtained are summarized in Table 2, and the values were derived from simultaneous equations formed by substituting in the equation values obtained from the experimental curves.

TABLE 2.

Anode voltage	k	Sensitivity, K	Theoretical sensitivity	Error
				per cent
350	1·118	0·828	0·841	− 1·5
320	1·04	0·917	0·920	− 0·4
280	1·112	1·063	1·051	+ 1·0
250	1·56	1·212	1·178	+ 3·0

The Cause of the Threshold Effect.

Having obtained a relationship between the threshold effect and the conduction current it is desirable to attempt some explanation of this effect. This can be done very briefly. As a current can be made to flow between the deflecting plates free ions must be in existence. These ions are produced by electrons in the cathode stream which has penetrated beyond the anode, partly by the escape of electrons from the stream and partly by collision with gas molecules.

All these electrons have quite a high velocity, so that, even when there is no potential gradient between the deflecting plates, some ions will reach them by their own velocity. If a potential difference is set up between the plates, however, a definite drift will be set up, electrons going towards the positive plate and positive ions towards the negative. The great difference between the mobilities of the two kinds of ions causes a concentration of positive ions, i.e. space charge, near the negative plate, thus causing the potential gradient to be greater over this part than over the rest. As the p.d. between the plates is increased, the potential gradient over the part occupied by the space charge does not increase so rapidly as that over the rest, owing to the limited supply of positive ions to form the space charge. Hence it is that when more than, say, 5 volts

is applied between the deflecting plates the deflection becomes proportional to the voltage. This is the value for 350 volts on the anode, but at 250 volts on the anode this figure is reduced to about 3·6 volts, bearing out Captain Eckersley's statement regarding exciting conditions.

does not alter between 0 and 10 000 cycles is useful, as this covers most of the range of audio-frequencies.

The Effect of Resistance on the Threshold Effect.

The effect of placing a resistance of 1 megohm in series with the deflecting plate is seen in Fig. 9. The

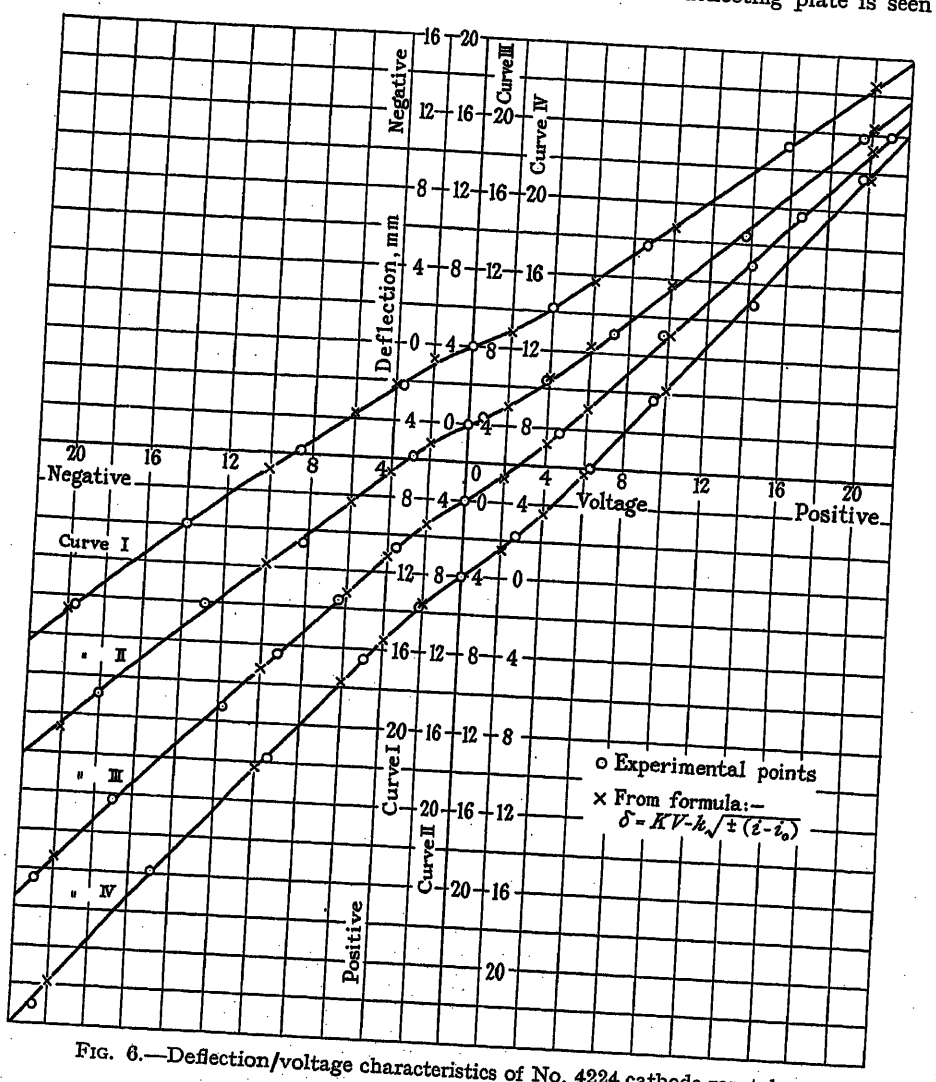


FIG. 6.—Deflection/voltage characteristics of No. 4224 cathode-ray tube.

The Effect of Frequency on the Threshold Effect.

A series of records were obtained connecting deflection and voltage with constant excitation for alternating voltages varying in frequency from 10 to 9 000 cycles per sec. The two lower frequencies were obtained from an alternator and the three higher from a valve oscillator. All five are set out together in Fig. 8, showing that all follow the same voltage/deflection curve as far as can be estimated. Consideration must be given to the fact that it was not possible to obtain all the records with the same scale relations between the two quantities, so that they all had to be reduced to a common scale in order to show them. It was not possible at the time to investigate the matter at still higher frequencies, but the knowledge that the effect threshold effect is apparently increased for positive deflecting voltages, but this is due entirely to the drop in voltage in the resistance. This is substantiated by evaluating the equation

$$\delta' = K\left[V \pm (i' - i'_0)R\right] - k\sqrt{\left[\pm (i' - i'_0)\right]}$$

and the values so obtained are shown on the curve. This also seems to indicate that the potential distribution in the space between the deflecting plates is dependent on the voltage applied to the plates and independent of the current flowing between the plates, for a given state of ionization in the tube.

The Characteristics of the 4224 Tube.

The connection between the various factors of tube

excitation when the electron stream is correctly focused is seen in Figs. 10 and 11. The decrease in the emission necessary when a deflecting voltage is applied is probably due to the removal, by the charged deflecting plates, alternating voltages, while with steady deflections some mean value of focus will have to be found.

The emission characteristics of the tube, Figs. 12 and 13, are those of an ordinary diode. Fig. 14 appears to indicate that the conduction current between the deflecting plates is proportional to the anode voltage for a given value of filament current, but Fig. 15 shows definitely that the conduction current is not independent of the anode current. The linear relation in the former is probably an accidental feature due to the emission current being near saturation value. It is a difficult matter to draw any definite conclusions, as they can only be based on the knowledge of the number of electrons reaching the anode, and not on that of the number passing through, these latter being those which are effective in producing the ionization, and so causing the conduction current.

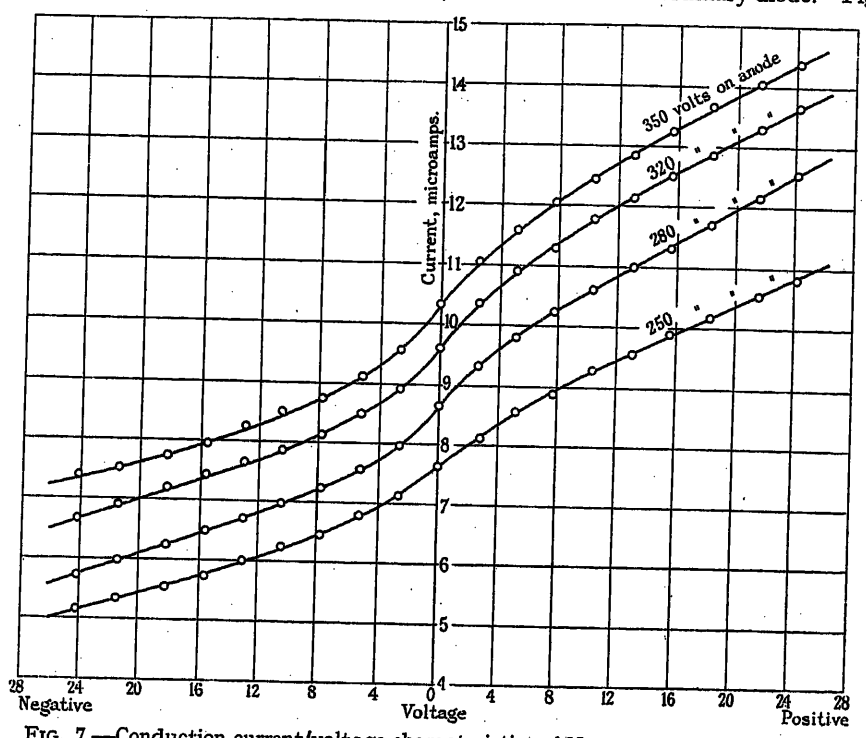


FIG. 7.—Conduction-current/voltage characteristics of No. 4224 cathode-ray tube.
These current curves are all displaced upwards by the presence of conduction currents external to the tube, but this current is independent of the deflecting voltage.

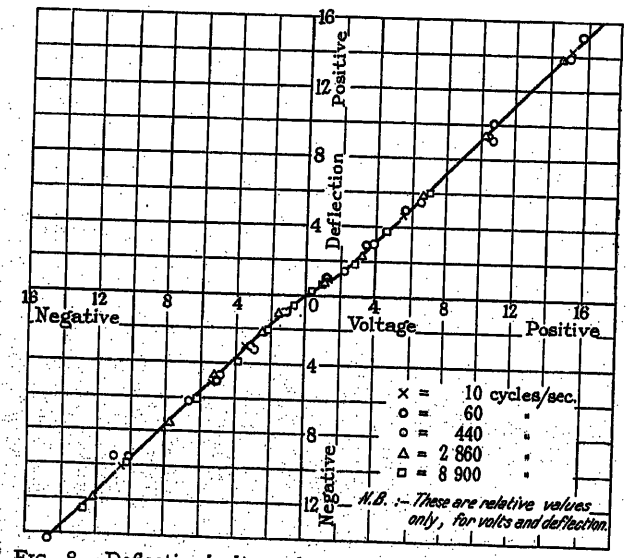


FIG. 8.—Deflection/voltage characteristic at various frequencies of No. 4224 cathode-ray tube. Anode voltage = 320.

of some of the ions surrounding the stream, so that the number of electrons in the stream must be diminished to restore a state of balance. The practical importance of this is that the electron stream should be focused with the deflecting voltage applied when used with

Method of Obtaining Most Accurate Results.

In view of the foregoing information the following suggestions are put forward as a guide when accurate work is being undertaken with this type of tube.

A correct calibration is essential, and this for preference should be done photographically, and should be carried out over the greater part of the surface of the fluorescent screen, and not only for two lines at right angles. This second precaution is made necessary by the presence of stray magnetic fields, and, if a magnet is used for bringing the spot to its zero position, large errors will result if it is neglected. It is not desirable to have to calibrate each time the tube is used, so that it must be used under the same conditions, one of these being that of position. The remaining conditions are those of excitation. Bearing in mind the large

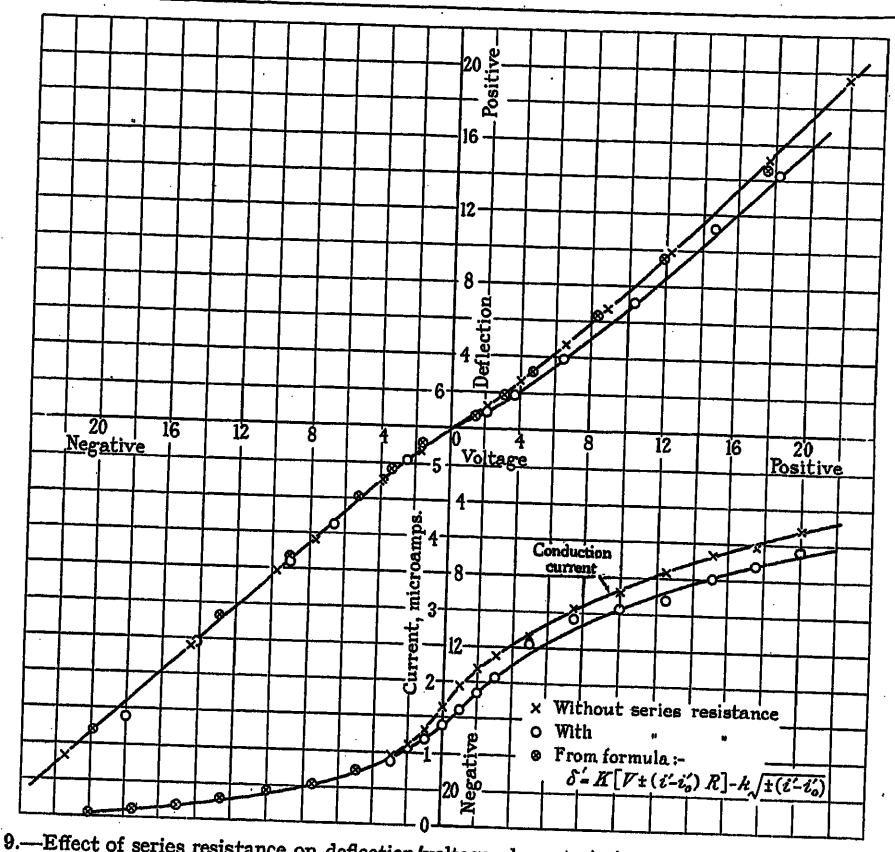


FIG. 9.—Effect of series resistance on deflection/voltage characteristics of No. 4224 cathode-ray tube.

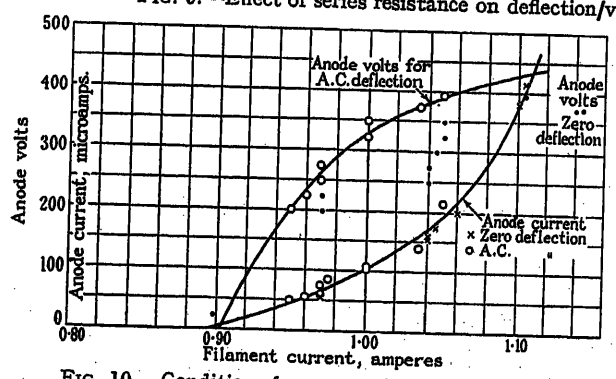


FIG. 10.—Conditions for correct focus of No. 4224 cathode-ray tube.

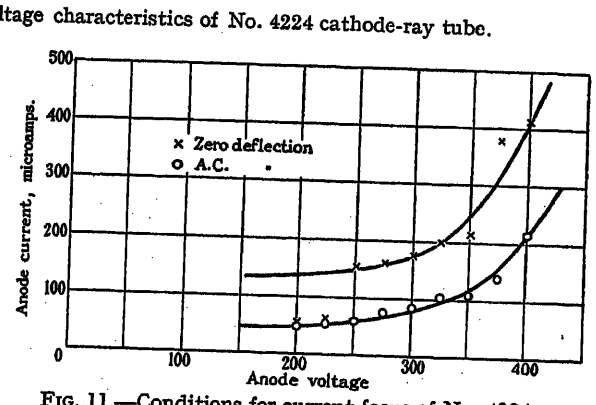


FIG. 11.—Conditions for current focus of No. 4224 cathode-ray tube.

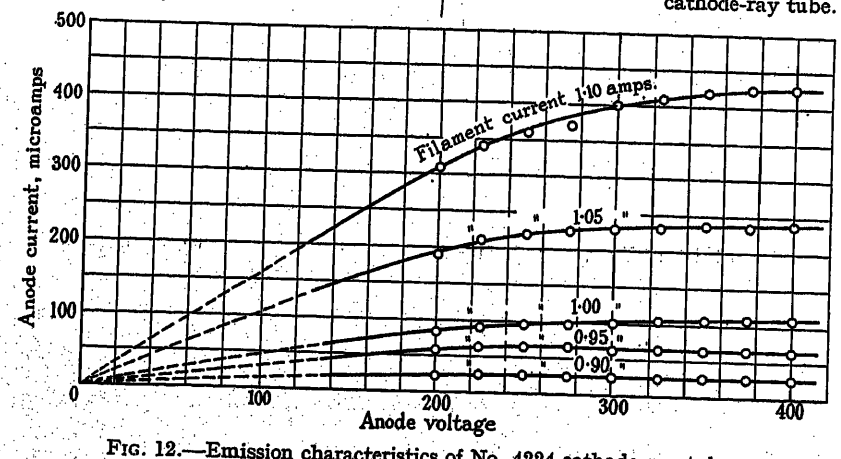


FIG. 12.—Emission characteristics of No. 4224 cathode-ray tube.

errors introduced by the threshold effect, the two factors which must be repeated exactly are the anode voltage and the conduction current between the plates, the first affecting the sensitivity, and the second the amount of threshold error. If the anode voltage is first fixed, the filament current can be adjusted to make the conduction current between the plates correct. As the emission current is only a measure of what is happening between the cathode and anode, and therefore can be only an indication of what happens beyond the anode, it is recommended that for the greatest accuracy the conduction current should be measured. This involves the use of a sensitive microammeter. With reasonable care it is possible to replace this by a milliammeter to measure the emission, but where a centralizing magnet is used it is essential that the field due to this should remain

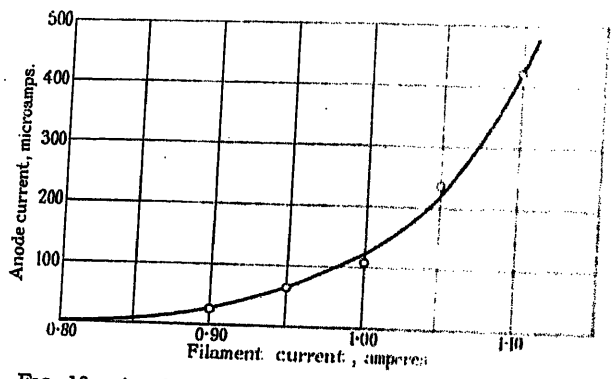


FIG. 13.—Anode current saturation curve of No. 4224 cathode-ray tube.

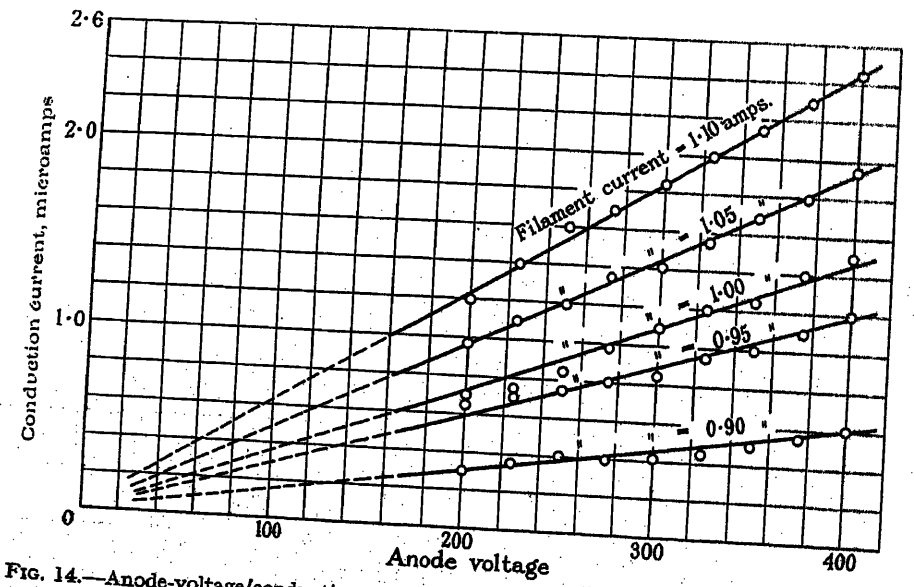


FIG. 14.—Anode-voltage/conduction-current characteristics of No. 4224 cathode-ray tube.

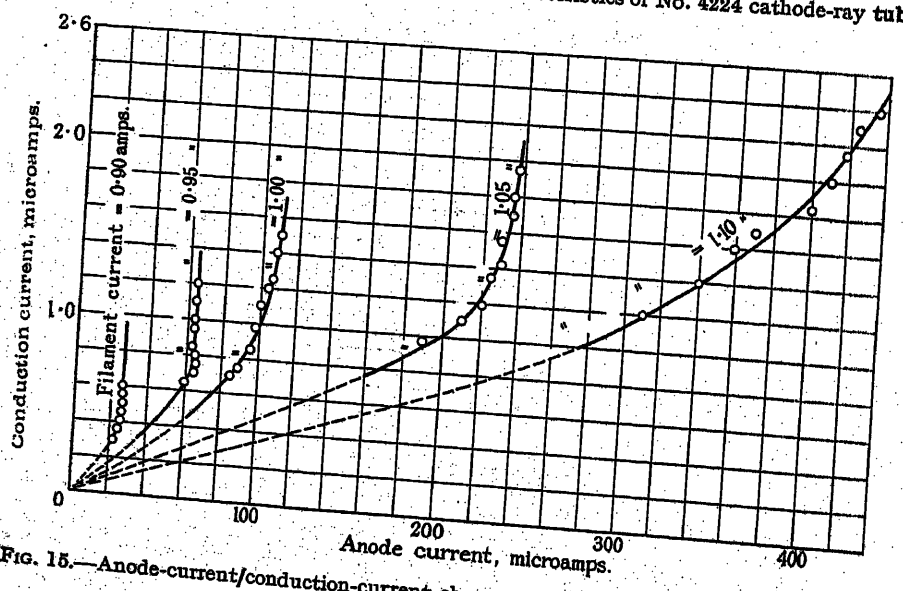


FIG. 15.—Anode-current/conduction-current characteristics of No. 4224 cathode-ray tube.

constant. It has been suggested* that the threshold effect can be overcome by deflecting the spot off the screen electrostatically and then bringing it back again by means of a magnet. The strong field from the magnet necessary to do this is seldom likely to be uniform, and consequently the image will be distorted. Owing to the beam striking the screen at an angle, a sharp focus will not be obtained.

A cathode-ray oscillograph built up from a tube costing under £6, and of less refined construction than the No. 4224 tube, has been in more or less continuous use for visual work during the past 12 months at East London College. During this period the calibration has not altered appreciably, while some 90 photographic records have also been made.

Conclusion.

In conclusion it is clear that valuable information could be obtained by still further investigation in this field. There is still need for knowledge of the effect of frequency, while the physical explanation of the threshold effect requires to be fully developed. The determination of the relation of the "space charge constant" k to the gas pressure and other controlling factors, would materially assist in the development of a sound theory.

A close study of the behaviour of hot-cathode tubes of many types extending over a considerable period leads the authors to the belief that the field of use of such apparatus will continue to expand more and more, especially in those cases where rapidity of response is essential. The simplicity of action, the ease of visual observation, and the absence of risk make the low-voltage tube an instrument of general utility in the laboratory. Correct interpretation of the results involves, however, an intimate knowledge of the principles underlying the action of such tubes.

The authors are glad to acknowledge here the debt they owe to Prof. E. H. Lamb for his kindness in loaning a Coradi co-ordinatograph for an extended period. Without this instrument it would have been difficult and tedious to make full use of the photographic records. Thanks are also due to the Council of the East London College for certain assistance from the Research Fund.

APPENDIX.

Particulars Relating to Later Pattern of Tube.

Introduction.

Since the completion of the paper, the Standard Telephone Co. have placed on the market a new type of tube, known as the "4018A" tube. The authors felt that if some facts concerning this could be added the scope of the paper would be materially widened and at the same time the subject would be brought more up to date.

The new tube is almost identical in construction to the older one, but it depends on a shield round the cathode stream for its focusing, and is designed for a higher anode potential. With this method of focusing, the size of the spot becomes independent of the filament current over quite a wide range, so that it is possible to use a high anode potential with a low filament current, thus reducing the magnitude of the threshold error and at the same time obtaining a brighter spot, which has also been still further improved by providing a better fluorescent material.

Typical Voltage/Deflection Graphs.

In Fig. 16 are shown four voltage/deflection graphs, whilst the corresponding conduction-current curves are given in Fig. 17. It will be seen that they are of the same general character as those for the 4224 tube, but it should be noticed that the deflection/voltage relationship for the 560-volt case is linear for negative voltages. At lower filament currents with lower anode voltages, the relationship is also linear and even extends to positive voltages, although the slopes of the positive and negative parts of the curve may be slightly different.

In order to make quantitative comparison easy, the threshold errors under various exciting conditions are given for both tubes. In the case of the 4018A tube, the filament current is higher than would be normally used with the lower anode voltages, so that the error would usually be less than this.

Table 3.

Anode voltage	Percentage error				4018A Tube	
	4224 Tube		4018A Tube			
	+ 20 V	− 20 V	+ 20 V	− 20 V	Theoretical sensitivity	Derived sensitivity
250	10·5	9·6	7·8	7·1	0·909	1·40
280	10·8	8·3	—	—	—	—
320	13·3	9·2	—	—	—	—
350	11·3	10·1	13·4	8·6	0·649	1·10
450	—	—	7·8	5·3	0·505	0·776
560	—	—	4·7	2·5	0·406	0·613

The error, which is the amount by which the experimental results fall short of the theoretical values, is less in the case of the newer tube than in the case of the older, due to the lesser ionization, because the emission current is reduced, and in addition it is understood that the quantity of gas in the tube is less.

The Sensitivity of the Tube.

On examining the curves of Fig. 16 some rather unexpected results are obtained, as shown in the last two columns of Table 3. The figures in the column headed "Theoretical sensitivity" have been obtained from the generally accepted formula

$$\text{Deflection} = \frac{V_d l_1 l_2}{2 V_a d} \text{ cm},$$

where V_d = deflecting potential,
l_1 = length of deflecting plate,
l_2 = distance from plate to screen,
V_a = anode potential,
d = distance between plates.

* F. Bedell and J. Kuhn: "Linear Correction for Cathode-Ray Oscillograph," *Physical Review*, 1930, vol. 36, p. 998.

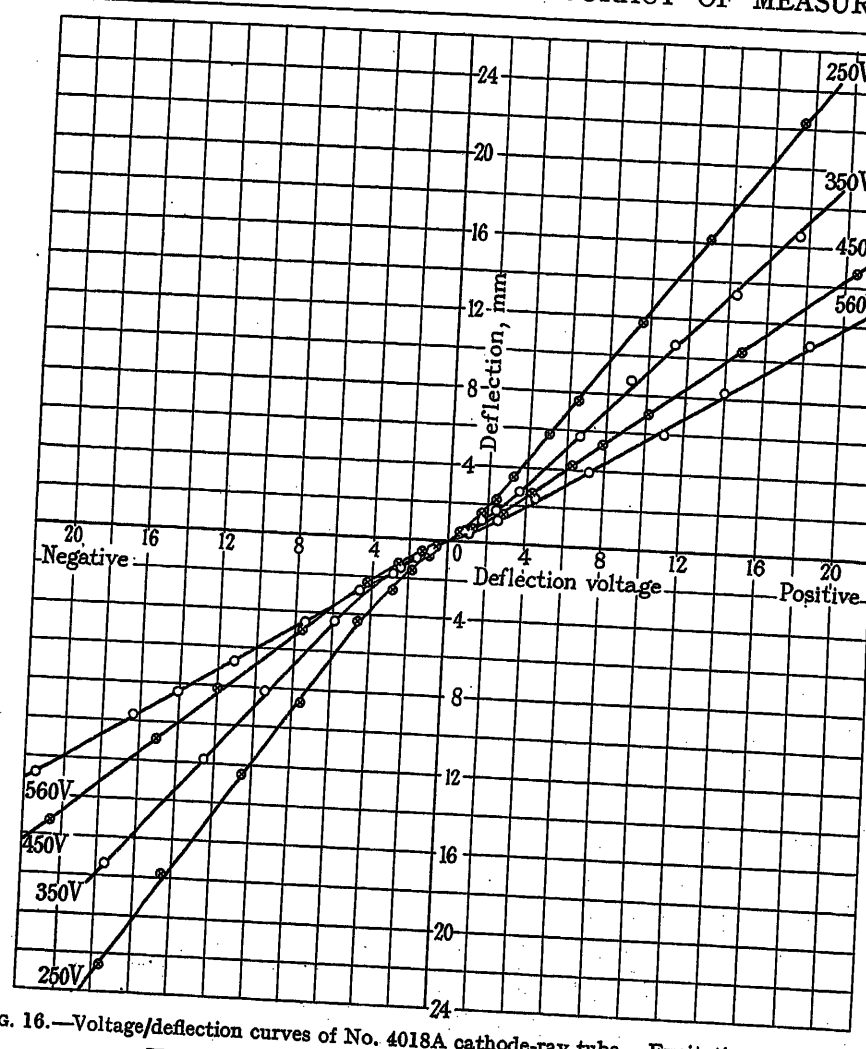


FIG. 16.—Voltage/deflection curves of No. 4018A cathode-ray tube. Excitation conditions:—

Anode voltage	Filament current	Shield voltage	Emission current
volts	amps.	volts	μA
250	1·22	10·5	36
350	1·22	12·5	45
450	1·22	16·5	50
560	1·22	35·0	74

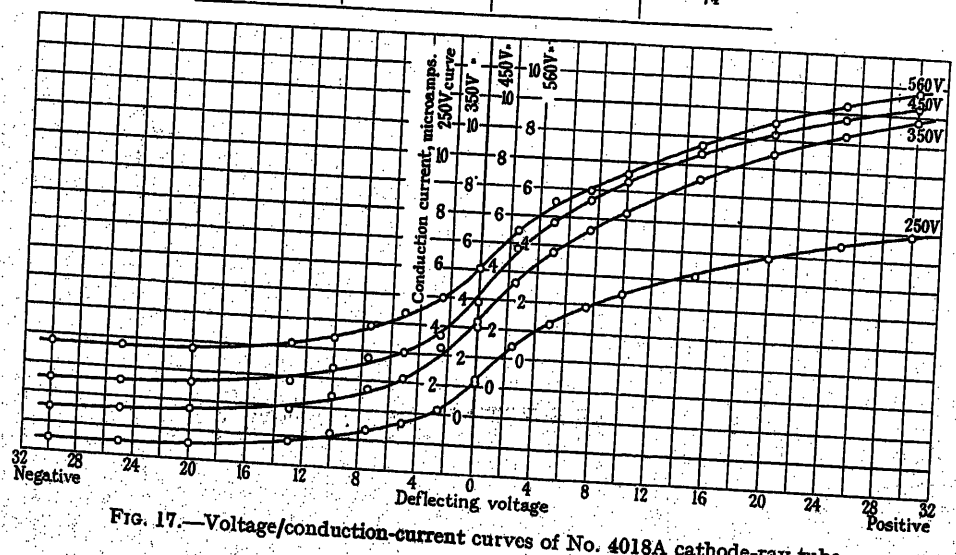


FIG. 17.—Voltage/conduction-current curves of No. 4018A cathode-ray tube.

while those in the last column have been derived from the experimental curves given, and are corrected to allow for the threshold error. It is seen that the tube has, the gas pressure in the 4018A tube is stated by the manufacturers to be one-tenth of that in the older pattern 4224 tube.

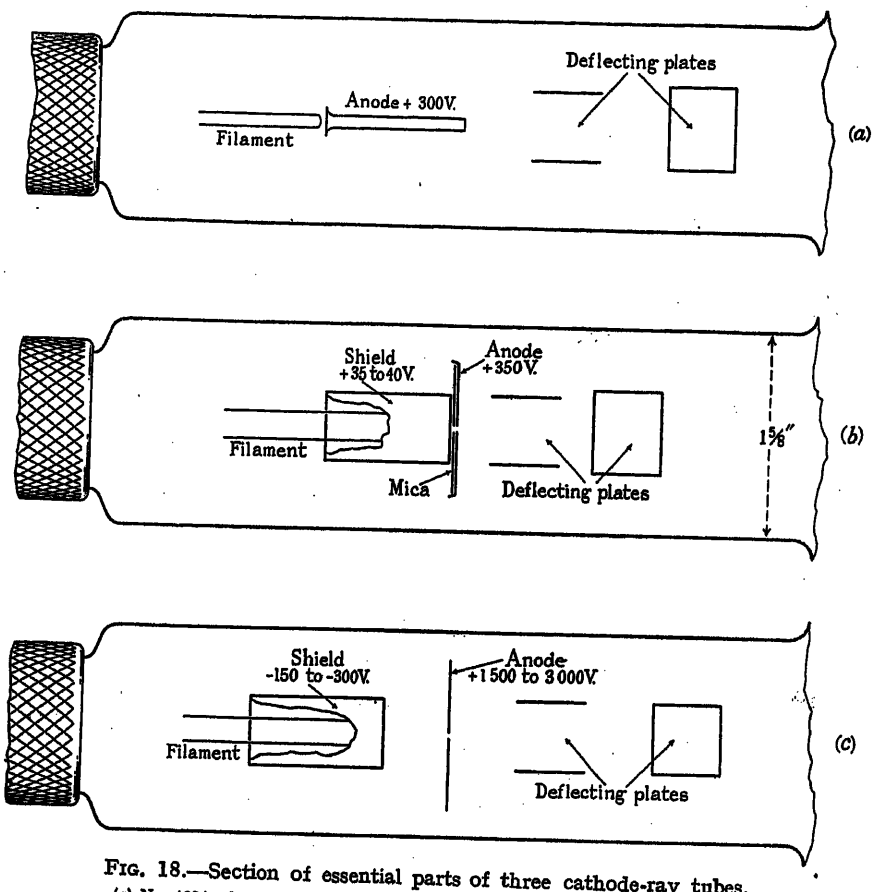


FIG. 18.—Section of essential parts of three cathode-ray tubes.
(*a*) No. 4224 tube. (*b*) No. 4018A tube. (*c*) Von Ardenne tube.

even when the decrease due to the threshold error is not allowed for, a sensitivity some 40 per cent higher than would be predicted by simple theory. This result has been confirmed by two other independent experimenters using the same tube. This difference is confirmed by the manufacturers who, when using another tube, obtained about 10 per cent difference. At present the authors are at a loss to account for this difference, and the matter is still under investigation.

A sectional view of the important parts of the several tubes under investigation is given in Fig. 18 with the appropriate working voltages. It should be noted that

To sum up, the following points should be noted in reference to the newer pattern of tube:—

(1) The possibility of obtaining a linear response of the spot to the deflecting voltage.
(2) A large increase in the average life.
(3) A brighter and better-defined spot.
(4) A reduction in the cost of the tube.

When due weight is given to these points, it will be clear that the field of use of the low-voltage cathode-ray oscillograph will be greatly extended.

[The discussion on this paper will be found on page 70.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 5TH FEBRUARY, 1932, ON THE PAPERS BY DR. WOOD (SEE PAGE 41) AND PROF. MACGREGOR-MORRIS AND MR. WRIGHT (SEE PAGE 57).

Dr. C. V. Drysdale: With regard to Dr. Wood's paper, the cathode-ray oscillograph is undoubtedly a tool of great importance. Within the last 10 years it has come more and more into vogue, and it seems obvious that its use will greatly extend in the future. Although the old types of oscillographs will still have a great field of application, the cathode-ray oscillograph has given us powers and opportunities of exploring phenomena which we could not have investigated by other means. The author has been the pioneer in this country of the hard internal-photography cathode-ray oscillograph, and he has not only given the instrument a simple and portable form but has also carried the details of the technique to a high pitch of perfection.

Turning to the paper by Prof. MacGregor-Morris and Mr. Wright, while there can be no question that the unsealed type of cathode-ray tube has many advantages as regards internal photography, it nevertheless involves always using a complete evacuating outfit. The fact that for each series of exposures one has to let in the air, withdraw the plates, and then evacuate again, militates against the portability of the apparatus. Furthermore, the advantage of having a tube which can be used for external photography is that it enables one to obtain a continuous record extending over a long time, whereas internal photography is only capable of a comparatively short range over a very small plate. When we were first concerned with the use of the cathode-ray oscillograph, I considered that a sealed form would be the ideal one, and more than 10 years ago I sketched out a design the main features of which seem to be almost identical with those of the von Ardenne tube. On the other hand, there are various difficulties associated with the sealed form of instrument. First, there is the question of the gradual decrease in the emission of the filament, which is not very serious; but I felt at the outset that the great difficulty in the way of the development of a sealed form of tube with sufficient intensity for external photography would probably be the luminescent compound. Unfortunately, luminescence under strong bombardment seems to be always accompanied by the disintegration of the luminescent material. All the luminous compounds which are used for luminizing dials have a fairly long life, but they do decay materially, and, naturally, the heavier the bombardment the greater the rate of decay. Only recently I saw a tube which had been in use for a comparatively short time; when it was switched on, the central portion of the fluorescent screen was seen to be less luminous than the remainder, probably owing to the fact that the illumination was more usually confined within that area. We really want a tube which we can seal and keep sealed for years. If we have periodically to open the tube, renew the luminescent screen, and re-evacuate, the advantage over the pump form is much less. An investigation with the object of obtaining luminescent materials of greater resistance to disintegration would be very valuable, not only in the case of the cathode-ray oscillograph but also in connection with luminous compounds. The radium or other exciting salt generally has a very long life, but the luminescent substance (e.g. zinc sulphide) begins to deteriorate after a comparatively short time. Concerning the relative value of hard and soft tubes, I think on the whole the advantage lies with the former. While soft tubes have certain advantages as regards sensitivity, ionization of the gas which they contain gives rise to many difficulties and errors, as Prof. MacGregor-Morris and Mr. Wright have described.

Dr. Wood has shown us how extremely sensitive the hard type of tube with internal photography is, and there is no doubt that for very high-frequency work we shall be forced to use this type for a long time to come. It is unfortunate, also, that even with the sealed tubes a record cannot be satisfactorily obtained without using very wide-aperture photographic equipment, which is costly and involves additional trouble in setting up. If we could only get a perfectly plane and very thin end to the tube there might be a chance of obtaining a sufficiently sharp image by means of a film running in close contact with it, and I think that this is what we should aim at achieving. One difficulty associated with most cathode-ray oscillographs is that of getting more than one trace. Dr. Wood showed one film on which there was a time trace, and I should like to know whether this trace was a simultaneous record. In oscillograph working it is very valuable to obtain not only a time trace but also a simultaneous record of two or three phenomena. How this can possibly be done by means of the cathode-ray oscillograph I do not see, but it is a problem to which those engaged on the subject should devote their best talents. It might, of course, be attempted by having two or more screened systems in the same tube, but the registration of the spots would probably involve difficulties.

Mr. J. E. Calthrop: I should like to make a few comments on the paper by Prof. MacGregor-Morris and Mr. Wright, with particular reference to the method of plotting the results. In view of the fact that the plates may be slightly inclined and hence the lines of force may be curved, there will be great difficulty in sending the beam through the centre, and I think the following method of plotting the results would be preferable. Taking a few figures from Table 1 as an illustration, I think we ought to plot for ± 2, ± 5, and ± 7 volts the mean deflections obtained. The positive voltages give rather large and the negative voltages rather small deflections, but in the case of the higher voltages the results come close together, and in order to find the law which is being obeyed we have to take the mean of the observations. This method gives a straight line which does not go through the origin, so that the expression for the deflection comes out to be

$$\delta = 0{\cdot}91(V - 0{\cdot}8)$$

I read off the deflections from the curves in Fig. 6, plotted them according to this plan, and obtained the following result. On plotting against V one gets for the four anode voltages a series of four straight lines which intersect at the same point (where $V = 1$ volt). I will not attempt to explain why this point does not fall at the origin; it seems, however, that the whole of the applied voltage is not really effective in deflecting the beam, so that the formula which is applicable is of the type:—

$$\frac{\delta}{V - V_0} = K$$

The deflection is also given by

$$\delta = KV\left(1 - \frac{V_0}{V}\right) \quad \text{or} \quad \frac{\delta}{V} = K\left(1 - \frac{V_0}{V}\right)$$

This equation shows that for low voltages the correcting factor is important, and therefore we must not expect the deflection to be proportional to the voltage. At higher voltages, however, the correcting factor becomes very small and the sensitivity approaches the expected value. As regards the variation of the sensitivity with the anode voltage, I plot S against $1/v$, where v = anode voltage and $S = \delta/(V - V_0)$ = sensitivity. Although sinple theory would lead us to expect a straight line through the origin, plotting the sensitivities as described above gives a straight line which does not pass through the origin, but which has an equation of the form:—

$$S = K\left(\frac{1}{v} - \frac{1}{v_0}\right)$$

By putting the two together I derive the following formula, which at least fits the author's observations.

$$\delta = K(V - V_0)\left(\frac{1}{v} - \frac{1}{v_0}\right)$$

This gives reasonably accurate values for the deflection, for any deflecting voltage and any anode voltage. This slide shows a typical calculation [Mr. Calthrop here exhibited a lantern slide], for which the equation is

$$\delta = 332{\cdot}5(V - 1)\left(\frac{1}{v} - \frac{1}{1\,750}\right)$$

Taking a point at random for which $v = 280$ volts, $V = 14$ volts, and $\delta = 13$ mm, I find that the calculation gives δ as 12·96 mm. Fig. A(b) illustrates the above treatment. I have recently been endeavouring to find an equation for the sensitivity curve which would take the above form for higher voltages and yet give no sudden discontinuity near the origin. The equation

$$\delta = KVe^{-V_0/V}$$

has been tested for one of the sensitivity curves, and has been found to fit the observations very well. This may be expanded, and only the first few terms of the resultant series retained. Thus

$$\delta = KV\left(1 - \frac{V_0}{V} + \frac{V_0^2}{2V^2}\right)$$

$$= K(V - V_0) + KV_0^2/(2V)$$

Hence for higher voltages, the equation takes the form found above. The advantage of this expression is that it shows the so-called zero-point anomaly not as a sudden discontinuity but as a bend near the origin, which straightens out more and more as higher voltages are

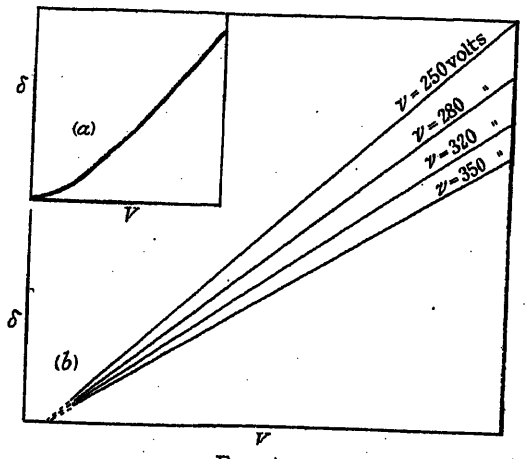


FIG. A.

(a) $\delta = KVe^{-V_0/V_0}$ (b) $\delta = K(V - V_0)$

approached. This curve is depicted in Fig. A(a). I do not know the theoretical explanation of this behaviour.

Dr. F. Simeon: I should like to ask Dr. Wood whether it is necessary with all types of photographic recording instruments to use the kind of silver-iodide plate which he has had developed at the Admiralty laboratory, and also whether this is a particularly difficult type to produce. Are these plates as difficult to make and as necessary for this kind of work as the Schumann plates are for ultra-violet photography?

Dr. T. E. Allibone: I shall refer first of all to Dr. Wood's paper. Speaking for those users of oscillographs who are engaged on the examination of transient phenomena on high-tension transmission lines of all voltage ratings and their effect on terminal apparatus, lightning arrestors, etc., I should like to say that for us the distinguishing and only valuable characteristic associated with oscillographs is their maximum writing speed. We are not interested in voltage sensitivity in general, because the transients which we observe occur on high-tension lines and therefore a sufficient voltage is always available; nor are we especially concerned with portability, since all the apparatus with which we deal, even if it weighs a few hundredweights, is easily transported in the field. Let us therefore consider for a moment the approximate writing speed which we need for recording transients. The figure can be arrived at by studying the records obtained on American transmission lines, on which much work has already been done. To obtain a clear photograph of a transient of 1 or 2 in. amplitude on a linear time-base of the order of a micro-second or less, we need a convenient writing speed of about 500 km per sec. If one wishes to work on the physics of spark-gaps, it will be preferable to have a shorter time-base than 10^{-7} sec. I have had experience of both low-voltage and high-voltage oscillographs. I found that the low-voltage type, such as that described by Dr. Wood,

was entirely unsuited to the transient phenomena which I wished to investigate, for the following reasons. In the first place, the energy of the cathode rays is too small, so that it is necessary to use special forms of Schumannized photographic plates; even so, the energy is still too small for high writing speeds. Incidentally, any form of special technique for dealing with photographic films is rather a disadvantage, because it complicates the operation of the oscillograph. Secondly, the electrostatic focusing of low-voltage electrons is inherently poor; it is no doubt influenced by the magnetic field round the filament, though this effect has been overcome by one or two ingenious methods. The use of hot cathodes in discharge tubes is also generally discredited, because the emission current from a suitably small area is too small and it is impossible to use a large area of emission since this will increase the minimum size of the spot on the plate. An advance in the direction of using hot filaments is only likely to come through the use of, for example, the ingenious device developed by Prof. Rogowski, who employs much higher temperatures for his emitting source and therefore obtains a much greater emission current without increasing the area of the source. The third disadvantage of the low-voltage oscillograph is that it dispenses with magnetic focusing of the beam, with a consequent loss of intensity. I cannot support Dr. Wood's remark with regard to the use of a solenoid to focus a beam of electrons. The mathematical treatment of the subject was worked out in 1928 by Busch,* who showed that such a solenoid has all the physical properties of a lens. Prof. Rogowski had observed the action of a solenoid (which must be short compared with its diameter) before Busch published the mathematical solution, and it is now well established that for a given distance between source and screen the solenoid allows a large angle to be used, with a consequent increase in the number of electrons. Finally, the intrinsic luminosity of a fluorescent screen is so much greater in the high-voltage oscillograph than in the low, that it is an easy matter to photograph this fluorescence with a camera. Attempts to intensify the ultra-violet light component emitted by the screen are of great value, since they enable a greater writing speed to be obtained; with the high-voltage oscillograph Rogowski has achieved writing speeds of several hundred kilometres per sec. The use of the Lenard window becomes possible with the high-voltage oscillograph, because the window can be as thick as 10^{-3} cm and can easily be obtained free from holes. Higher electron energies enable one to use asymmetrical circuits for deflecting the electrons, an important feature from my point of view. To observe the magnitude of a surge on a transmission line, one of the pairs of deflecting plates in the body of the oscillograph is connected through the potential divider to the line, the other being connected to earth, and the resultant electrostatic field between the plates is a measure of the surge voltage. In asymmetrical circuits one is liable to encounter difficulties in connection with the beam of electrons, because one of the plates is at the potential of the case and the other is not. These difficulties become less as the speed of the electrons is increased. Using 75 kV on the discharge tube of the oscillograph, Prof. Binder (of Dresden) has been able to apply 100 kV to the deflecting plates of the oscillograph. Dr. Wood remarks that Knoll has dispensed with magnetic focusing. This is true in so far as it applies to the discharge tube, where both Knoll and Binder have developed good electrostatic focusing, but they use a solenoid to focus the electrons between the anode and the photographic plate. Rogowski maintains that better results can be obtained with two solenoids. Fig. B is an oscillogram of an impulse lasting a few micro-seconds. In this case the electron beam is switched on to the photographic film just at the moment when the transient arrives. A very short time afterwards two other calibrating records are added to the picture: (*a*) the permanent voltage on the deflecting plates, and (*b*) a time scale measured in micro-seconds. These are recorded by mechanical switching, but it could be done electrically. The impulse is applied to a point-plane spark-gap set for 700 kV; the voltage rises to a maximum, is maintained almost constant,

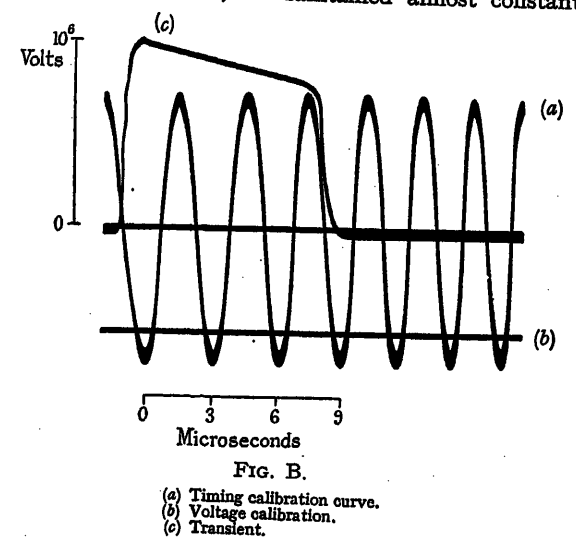


FIG. B.

(*a*) Timing calibration curve.
(*b*) Voltage calibration.
(*c*) Transient.

ionization occurs in the gap, and breakdown ensues after about 9 micro-seconds. A resistance is placed in series with the impulse generator so as to vary the rate of rise of voltage. The voltage rises in 0·5 micro-second, which represents a moderately slow impulse, and decays to half value in 20 micro-seconds. [Dr. Allibone here exhibited an example of high-speed writing recording, the pictures having been taken in 0·4 micro-second.]

With reference to the paper by Prof. MacGregor-Morris and Mr. Wright, if in the case of the sealed-off type of oscillograph it was very necessary to get rid of the threshold effect, could not this be done by separating the deflection plates from the discharge-tube portion of the oscillograph by means of a diaphragm with a small hole in it and maintaining a difference of pressure between the two chambers of the oscillograph by means of a sealed-on pump?

Mr. J. F. Herd: With regard to Dr. Wood's paper, I think the author's classification of oscillographs into two groups, high-voltage and low-voltage, is rather arbitrary, and that in his presentation of the case he does not pay sufficient attention to the medium-voltage

* *Archiv für Elektrotechnik*, 1927, vol. 18, p. 583.

sealed-off type, for which there is undoubtedly a great future and a wide range of uses. It could be made as convenient in operation as the ordinary wireless valve. In fact, with properly-designed auxiliary apparatus, it has now practically reached that state. The medium-to-low-voltage oscillograph is numerically the most important, even if we impose the distinction that an instrument which is limited to visual observations should really be called an " oscilloscope." The same tube may well be used for both low and medium voltages, the main point of difference being the material of the fluorescent screen. Incidentally, I think the author wrongly describes as " phosphorescence " what should rather be termed " fluorescence." In the present state of fluorescent materials a sealed-off low-voltage tube would be primarily used for visual observations or the photography of quasi-stationary images, and zinc silicate seems to be the best material for the screen. The great increase obtained in the intensity of fluorescence on increasing the voltage from 300 or 400 volts to 3 000 or 4 000 volts gives the medium-voltage tube a wide field of use in many forms of external photography and as an oscilloscope. With regard to the advantages of external photography with a medium-voltage tube, on one occasion we obtained 1 100 records in a recording period of only 4½ minutes, whereas using visual methods on precisely the same type of work our previous speed was about 150 to 160 records per hour. It would undoubtedly be an improvement if medium-voltage tubes could be made with higher vacua, thus minimizing many of the ionization problems which arise. Other desirable improvements in the tube are more sensitive fluorescent materials and greater sharpness of the spot. External photography has of recent years greatly benefited from the development of lenses and of film-emulsions for cinema purposes, but improvements are still possible, especially in the lens system. One other possibility, to which reference is made in the paper, is that of a quartz end—or even a quartz window over a limited portion of the end—to permit of better penetration of the fluorescence. For instance, calcium tungstate has a fluorescence which extends well into the ultra-violet, and obviously a great deal of this may be lost in a glass tube and glass lens-system. The fact that a voltage of 3 000 to 4 000 volts is required to operate these tubes is not a serious difficulty, because the anode currents are so small that they can be derived from an eliminator of simple type. The currents are generally much less than 1 mA, and a half-wave rectifier with simple smoothing system is quite sufficient. Considerable advances have recently been made in the construction of oscillographs, some of these being embodied in the new low-voltage instrument produced by Standard Telephones and Cables, Ltd., the medium-voltage oscillograph due to von Ardenne, and the model on generally similar lines developed by the Edison Swan Electric Co., Ltd. A new British oscillograph intended for either low-voltage or medium-voltage operation has also recently been produced by Messrs. A. C. Cossor, Ltd. I have used an oscillograph of this type quite satisfactorily at all voltages from 300 or 400 volts up to over 3 kV. I think the list of references in Dr. Wood's paper should include a paper describing a new time-base circuit, using a mercury-vapour valve, due to A. L. Samuel.* Another recent bibliographical addition is a paper† by J. B. Johnson on the general theory and uses of cathode-ray oscillographs. In connection with single-traverse time-bases, I have had occasion recently to use a simple method employing a condenser with a saturated diode, after the manner of the recurrent base shown in Fig. 7 of Dr. Wood's paper. The arrangement is shown in Fig. C. The condenser C is charged by the battery B, deflecting the spot to the left side of the oscillograph screen. Release of the key K allows the condenser to discharge through the diode D in a manner that can be caused to follow a law practically linear with time. During this period the spot travels in a corresponding manner across the screen, giving a timing voltage for any transient phenomena applied to the other pair of plates. The battery B_1 serves to maintain saturation of

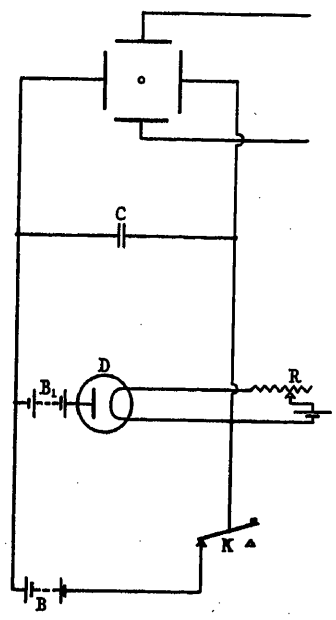


FIG C.—Circuit for single-sweep linear time-base

the diode, with consequent improvement of linearity. The speed of the time stroke is governed jointly by the capacitance of C and the adjustment of the diode filament, and is capable of a wide and easy range of control.

With regard to the paper by Prof. MacGregor-Morris and Mr. Wright, I am particularly interested in the threshold effect mentioned by the authors. I think a rather better name for it might be " origin-distortion." We have a neat method of testing for it by means of apparatus developed for another purpose. This is a potentiometer giving voltages proportional respectively to cos θ and sin θ on the two pairs of plates, as θ is varied in 10-degree steps. When the potentiometer is supplied with alternating current this gives a pattern in the form of a line tilted to the vertical axis at the angle θ. Rotation of the potentiometer revolves the line and reveals this type of distortion wherever it occurs. I have noticed that, among a batch of otherwise similar

* *Review of Scientific Instruments*, 1931, vol. 2, p. 532.
† *Bell System Technical Journal*, 1932, vol. 11, p. 1.

tubes, many show an abnormal amount of distortion in those quadrants which lie adjacent to the vertical deflection. The ionic-cloud theory to which reference has been made is no doubt largely substantiated in practice, but I doubt whether it represents the whole of the story. To give a concrete example, when using one of the Standard Telephones and Cables "4018A" tubes referred to by the authors I found that with a certain filament current and anode voltage which gave an excellent visual focus, the potentiometer method showed no trace of origin-distortion. If the focus was reset by increasing the filament current and readjusting the shield voltage, a well-focused spot was obtained, coupled with definite origin-distortion. As regards the effect of magnetic fields, when calibrating the tube one must ensure first of all that the spot is in a uniform field. Secondly, if the calibration is one which, for its use, demands that the spot should be restored to a certain position, it is essential that it should always be returned by means of precisely the same field as was used for this purpose at the time of the calibrations. An excellent method of shielding these small tubes from stray magnetic fields, including that of the earth, is by means of a mumetal screen, or, more cheaply, with an ordinary piece of drainpipe! As regards the difficulty mentioned by the authors that the von Ardenne tube necessitates the use of a third voltage, this is not a serious drawback if the tube operates with a negative cylinder, since the third voltage can be obtained without any increase of current-load by the well-known method of introducing a bias derived from a resistor joined between the cathode and the h.t. negative return lead. I have used this arrangement regularly both with von Ardenne oscillographs and with the new Cossor oscillograph, and have found it to be very satisfactory in operation.

Mr. G. A. Whipple: In view of the rapidly increasing demand for cathode-ray oscillographs of all types, it would be useful to formulate some definite standards by means of which the relative capabilities of various types of tubes could be judged. Such standards would be of service to both the user and the manufacturer. Setting aside considerations of cost and auxiliary apparatus, the criteria by means of which the user selects a tube are voltage sensitivity and photographic sensitivity or maximum linear recording speed, both these figures of merit being given at a stated accelerating potential and with stated anode and conduction currents flowing. The voltage sensitivity is readily determined, and is stated in millimetres per volt on the deflecting plates. The photographic sensitivity seems to present a more difficult problem. Some manufacturers and workers maintain that their tubes will record up to certain stated frequencies, an assertion which has no meaning until the amplitude of the wave and the width and intensity of the trace have been specified. What is required is a specified maximum recording speed corresponding to a certain defined blackening of the photographic surface at this speed; in fact, a recording speed formulated on the basis of a standard oscillogram relative to which any given oscillogram will have a figure of merit. M. Knoll* has comprehensively defined maximum linear recording speed. The first step is to take a definite minimum darkening of the photographic plate. This intensity of darkening is derived photometrically and should be given by

$$\log_e (I_0/I_T) = 0{\cdot}1$$

where I_0 and I_T are the intensities of light transmitted through the unaffected and the trace-darkened portions of the photographic negative respectively. Then, assuming always that this photographic intensity condition is fulfilled, the standard oscillogram is taken as one having a ratio of amplitude to trace width of 50 : 1. If a recording speed of $r_{max.}$ is attained on any oscillogram, say by impressing a square-peak travelling wave on a line of known length and measuring the speed from the record of the wave front, then the true maximum linear recording speed ($r_{s\,.\,max.}$) referred to standard conditions is given by

$$r_{s\,.\,max.} = r_{max.} \times \frac{1}{50} \times \frac{a}{d}$$

where a is the amplitude and d the width of the trace. It would be of interest if Dr. Wood or Prof. McGregor-Morris could suggest methods by means of which the performance of cathode-ray oscillographs could readily be judged.

Mr. F. S. Robertson: With regard to the paper by Prof. MacGregor-Morris and Mr. Wright, their statement that some of the errors of manipulation are due to charges on the walls of the tube is borne out by the fact that in experiments where very highly-exhausted quartz tubes are employed it is often necessary to place earthed metal shields round the inside of the tube in order to prevent effects due to electrons which may otherwise become attached to the inner wall. If in these cases the screen is put outside instead of inside the tube, the effect is often worse than with no screen at all. The authors have clearly shown that the so-called "threshold effect" is not really a threshold effect in the true sense of the word. Any phenomenon which makes the potential gradient in volts per cm over the centre portion of the space between the plates less than (Volts applied to plates)/(Distance between plates) is likely to cause this effect. What we have to consider is not merely the potential gradient in volts per cm, but the volts per cm in the vicinity of the cathode ray per volt applied to the plates. The force acting on the electron is determined by the true potential gradient. Any effect such as space charge or difference of contact potential due to dissimilar conditions at the surfaces of the plates, which will cause the true potential gradient in the vicinity of the cathode beam to be less than (Applied voltage)/(Distance between plates), will cause the true potential gradient per applied volt to be small for very small values of the applied voltage but after passing zero applied voltage to increase rapidly at first and then to become practically constant for the larger values. The authors seem somewhat diffident in pressing their explanation as they find that the effect persists even at frequencies of the order of 10 000 cycles per sec.; but, after all, the effect is due to moving electrons, for which the necessary speed would be a matter of small consideration.

Mr. R. Mines: I should like to refer to the von Ardenne

* *Zeitschrift für Technische Physik*, 1931, vol. 12, p. 54.

tube, which I have had occasion to use. In connection with the ionic focusing, at a high velocity of traverse of the spot one can observe a blur which is produced by the continuous movement of a very much finer spot. It is suspected that this phenomenon is actually taking place all the time. In recording 10 000 cycles per sec. with a wavelength and an amplitude on the record of about 1 cm, one can definitely observe that the spot has an epicyclic (or hypocyclic) movement; it moves in a circle as though in the ionic focusing process the beam of electrons were rotated about an axis. It is highly desirable to eliminate this rotation for the purpose of recording at high speeds. If the rotation can be eliminated, this tube is capable of giving a very fine trace. Using these tubes we have observed the phenomenon of failure of the screen material. When a voltage up to the maximum recommended by the makers (4 000 volts) is used, a few seconds' exposure to the stationary spot will cause a brown or even a black spot to appear on the white screen, which loses its fluorescence at that particular point. In practice this trouble is evaded by making sure, in the case of single-trace recording, that the spot never remains stationary on the screen, or else by focusing the spot near the edge of the screen and setting the time-scale deflection so that it traverses a piece of clean screen afterwards. It would be an advance to produce a fluorescent material which is not subject to this disadvantage. In connection with external photography, I have successfully employed a photographic lens having an aperture of $f/2{\cdot}9$. This is much larger than the size of photographic lens usually available, and due to its being very accurately corrected it costs a good deal in comparison with the total outlay on the oscillograph equipment. A cheaper form of lens, less highly corrected, with either one or two pieces of glass (perhaps plano-convex), might be good enough for the purpose, however. Such a lens could be made with a bigger aperture, even as large as $f/1{\cdot}0$. Dr. Allibone suggested dividing the tube into two compartments by means of a diaphragm of small aperture, the compartment in which the deflecting plates are placed being exhausted to a higher vacuum so as to eliminate the threshold effect. It seems to me, however, that in the tubes where this effect occurs it is impossible to apply such a device, because the essential point of the method of ionic focusing adopted in such tubes is that the cross-section of the ray is kept down to a low value throughout the whole length of its path. If that constraint is relaxed over two-thirds of its path, or at any rate over its path between the deflecting plates and the screen, obviously it will be impossible to prevent the scattering which it is desired to avoid. If a single trace of the spot is used, when the spot is deflected off the screen it is found to be necessary to ensure that its deflection is many times the diameter of the latter. If the ray is deflected so that it glances on to the side walls of the tube, reflection of the electrons takes place to a very considerable extent and causes illumination of the screen and fogging of the exposed plate. If the ray can be bent round so that it strikes the parallel and not the conical portion of the tube, at an angle approaching 90°, this effect causes no trouble.

Prof. J. T. MacGregor-Morris: I should be glad if Dr. Wood would put forward his views on the focusing system of the new Standard Telephones and Cables type of tube. The difference between the new tube and the von Ardenne type is that whereas in the one the focusing cylinder is positively charged, in the other it is negatively charged. In 1928, at Purdue University, I had the privilege of examining Mr. R. H. George's electrostatic focusing tube, the negatively-charged cylinder of which was moved up and down by means of a rack and pinion, so that one could focus the cathode beam as easily as a microscope. In connection with phosphorescent materials, I should like more information regarding the statement that "Rogowski and Ruhlemann obtained at 55 kV a value of 35 lumens per watt for the luminous output of the screen of a high-voltage tube." This is nearly equal to the efficiency of an arc lamp. Can we regard the cathode-ray tube as ultimately becoming an efficient source of light? In connection with the capacitance of the leads and deflecting plates of the oscillograph, recent measurements of the dielectric losses in liquids appear to indicate that the losses in the leads and plates amount to about one-fifth of the total loss, and, therefore, if cathode-ray oscillographs are to be used at very high frequencies this factor will have to be carefully considered. In conclusion, the author refers (page 54) to a simple switch the contact arms of which fall into mercury cups. Many years ago I used this arrangement for rather lower speeds, and I found that when the contact arm first made contact the mercury rebounded, and broke and remade the circuit two or three times.* A mechanical extension was applied so that this was permanently in the mercury, with the result that when the actual electric contact entered the mercury it closed the circuit satisfactorily.

Dr. A. B. Wood: In the Summary to their paper Prof. MacGregor-Morris and Mr. Wright state that the chief part of the paper deals with what is known as the "threshold effect," and then they give a theory of this effect which is based on the fact that the tube contains gas. I think a better title for the paper would have been "Accuracy of Measurements made with Gas-Filled Cathode-Ray Tubes." Their remarks about the threshold effect do not apply to high-vacuum tubes. The general explanation of the focusing action in gas-filled tubes is that a column of positive ions is formed along the axis of the beam and that a diffused cylinder of negative electrons surrounds it, thereby producing a radial field which focuses the beam. If this is the correct explanation, would it not be much simpler to use a high-vacuum tube, which has no complicated gas corrections, and a simple focusing device consisting of a thin positively-charged wire running down the axis of the tube, surrounded for some distance by a negatively-charged cylinder? The latter should then have the same effect in a hard tube as the gaseous ionization has in a soft one.

Mr. L. H. Bedford (*communicated*): The opinion that the "inter-plate current" in the gas-filled cathode-ray oscillograph is due solely to ionization seems to be quite generally held, but the following facts are sufficient to show that this view must be erroneous. (*a*) The "inter-plate current" persists practically unaltered in a high

* See *Electrician*, 1907, vol. 59, p. 292.

vacuum. (*b*) The mean free path of the electrons is usually several times the length of the bulb, from which it may be deduced that the amount of ionization is not nearly sufficient to account for the observed plate currents. (*c*) The currents remain "electronic" even for quite high negative plate voltages (see Fig. 7 of the paper by Prof. MacGregor-Morris and Mr. Wright). We believe that the explanation of these facts will be found by following up a point which has largely escaped attention in the literature of the subject. This is the question: How do the electrons which pass through the gun get back to it? In the early days this point was slurred over by saying that, in the first place, only a very small proportion of the electrons actually passed through the gun, and those which hit the screen got home partly by leakage over the glass and partly by ionic conduction. This argument is quite fallacious, more especially when applied to modern tubes with disc anodes and Wehnelt-cylinder focusing; for in these tubes it is quite possible for the entire anode current to go through the gun hole and down the beam. Since the mean free path is several times the length of the bulb there are only enough ions to take care of a small proportion of the current, and this leaves far too big a residue to be accounted for by leakage. The true state of affairs appears to be that the electrons get home by means of secondary emission from the fluorescent screen. If this is the case, then, since the number of secondary electrons falls off to zero as the speed of the primaries is reduced, we should expect to find that on progressively reducing the gun voltage a point would be reached where the tube would suddenly fail to function; this is actually observed, and the mode of failure is exactly in accordance with the supposition that the screen is piling up negative charge. Accordingly it is suggested that what has been looked upon as "inter-plate current" would be better described simply as "plate current." When one of the plates has its potential changed, what happens is really a redistribution of the return space current amongst the four deflector plates and the gun. In the Cossor oscillograph, which was referred to in the discussion by Mr. Herd, this state of affairs is recognized and the anode is provided with a shielding extension which embraces the deflector plates as completely as possible and intercepts a very large proportion of the return space current. The effect of this shielding is very striking (see Fig. D). It will be noted that the plate current is very greatly reduced and the ionic current is no longer masked by the electronic current, but shows up clearly on the negative side. The fact that "origin distortion" still persists with this tube in spite of the much reduced electron plate currents, indicates that the space-charge effect is ionic and not electronic in character, a conclusion which was also reached independently by calculation; the electrons produce no measurable space-charge effects of this sort. An attempt has been made to investigate mathematically the matter of origin distortion, but in its complete form the problem was found intractable. However, a good deal of light can be thrown on the problem by considering it in the following manner. The electron beam passing between the plates may be regarded as a virtual emitter of ions and electrons; owing to their high mobility the latter produce no measurable space-charge effects and they may be ignored for the present purpose, but of the former we may inquire what negative voltage on a deflector plate is required to "saturate" this virtual ionic emission. Unfortunately, even now matters are too complicated to allow of an accurate solution, but by means of sufficiently violent approximation one may arrive at least at the order of the effect to be expected. Curiously enough, a first calculation gave a "threshold value" of 5 volts, exactly the figure arrived at independently by Prof. MacGregor-Morris and Mr. Wright. The term "threshold value" is here exactly appropriate, for it is that value of deflector-plate voltage which is required before any field appears at the beam. Actually, of course, this treatment is only approximate and the threshold value is no more sharply defined than is the transition from temperature to voltage saturation in a diode. That this view of the threshold effect is substantially correct is confirmed by the observation that the effect decreases with reduced gun current and with increased beam diameter, the latter being measured in the neighbourhood of the deflector system. A beam which is very thin where it passes through the deflector plates gives a much more pronounced threshold effect than a thicker beam carrying the same current. Unfortunately, a thin beam is necessary for other reasons, and a compromise has therefore to be made. Reference was made in the discussion to the longitudinal effect of deflector-plate voltage. This is usually only observable when very large deflections are involved, but in any case it can always be completely suppressed by operating the deflector plates symmetrically in push-pull, a point which adds to the already known advantages of tubes in which all four deflector plates are brought out separately. Mr. Mines mentioned that he had observed certain types of internal oscillation in the oscillograph

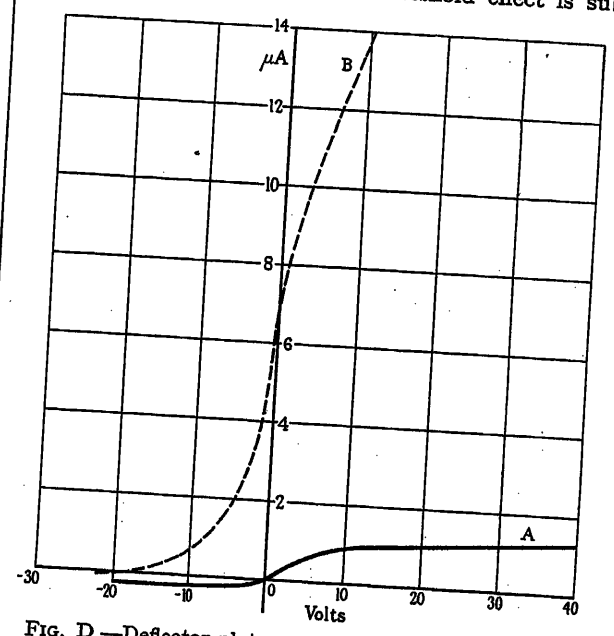


FIG. D.—Deflector-plate current at 50-μA gun current.
Curve A. Shielded structure.
Curve B. Similar structure without shield.

tubes. We have experienced more than one variety of this effect, and have found that it appears to be associated with glass charge effects in the neighbourhood of the deflector plates, and particularly on the portion where the conical part of the bulb joins the parallel neck. A piece of tinfoil wrapped round this portion will generally stop these oscillations. In the case of the Cossor tube it was found necessary to extend the anode shield beyond this portion in order to suppress oscillations completely without resorting to external shielding. Although this appears to effect a complete cure of the trouble, we are really at a loss to visualize the mechanism of these oscillations.

Mr. R. Davis (*communicated*): I should like to supplement to some extent Dr. Wood's remarks on the development in the design, and the technique of the use of, the cathode-ray oscillograph for high accelerating voltages. The first step in this direction was taken by Dufour. He was followed by Norinder in Sweden, and soon after by Rogowski and his co-workers in Aachen, and Gabor in Berlin. Their instruments were similar generally in design. The discharge tube was of glass and the rest of metal. Accelerating voltages of 60 to 70 kV were used, with a cold cathode, and the cathode current was of the order of 1 mA. In order to have as high a vacuum as possible in the deflection chamber and sufficient gas in the discharge tube to provide the requisite cathode current, the oscillographs were operated with two separate vacua; continuous pumping was resorted to in the deflection chamber, while the gas pressure in the discharge tube was controlled by a suitable leak. It was found that the gas discharge tube was not always suitable for continuous operation. The glass walls near the cathode developed surface discharges leading to irregularity in the cathode stream. Further, the electron discharge caused heating in the discharge tube with a release of gas molecules, and a consequent fluctuation in the discharge-tube vacuum. This led to the use of the metal discharge tube, or its equivalent, by Berger, who required the oscillograph for continuous operation in lightning studies on transmission lines. Knoll, in Berlin, also used the metal discharge tube and furthermore made a success of external photography through a Lenard window, as described by the author. Knoll was able to dispense with the fore concentrating coil used by Rogowski, and to achieve similar results largely through being able to use a much larger cathode current. Further improvements in this construction consisted of mechanical refinements whereby the deflectional sensitivity could be varied under vacuum, and in addition the shape of the deflection plates was designed to give maximum sensitivity. Later, Binder and his co-workers produced a cathode-ray oscillograph which consisted of a large metal tube 30 cm in diameter and about 2 metres long. The discharge tube was at one end of the tube, separated from the rest of the oscillograph by a suitable diaphragm. The high voltage applied to the cathode was brought in through a porcelain bushing. The advantage of this type of tube over the previous metal discharge tubes was (*a*) the large volume, which prevented sudden fluctuations in the pressure, (*b*) the remoteness of the walls of the tube, and their disturbing effects, from the cathode, and (*c*) the fact that the field through which the beam passed was approximately uniform. To localize the discharge on the surface of the cathode, a cylindrical electrode, the potential of which was left floating, was placed concentrically with it. An additional important feature of this oscillograph was the design of a pair of ordinate plates for a voltage of 200 kV. Previously the deflecting plates of oscillographs had been designed for voltages of from 5 to 10 kV. With deflection plates for this high voltage much work can be carried out without the aid of voltage-dividers and their attendant sources of error, and the properties

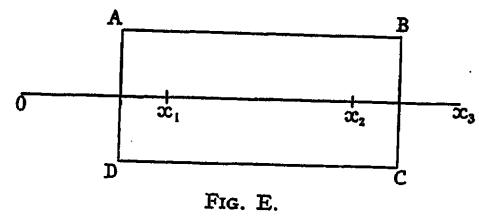


FIG. E.

of dividers for use in registering very rapid transient phenomena can be investigated practically. On the question of recording technique, the author outlines some of the methods which have been used for synchronizing abscissal and ordinate deflection so as to enable a satisfactory record to be obtained on the photographic plate. The function of the timing circuits in recording single transients is to move the beam from some position O (Fig. E) so that at the onset of the transient it takes up a position such as "x_1" on the photographic plate ABCD. During the time occupied by the transient the beam moves from "x_1" to "x_2" at a constant abscissal speed, this speed being controlled by the time-constants of the timing or abscissal plates. Their subsequent motion in the abscissal direction takes the beam to the position "x_3." Arrangements must

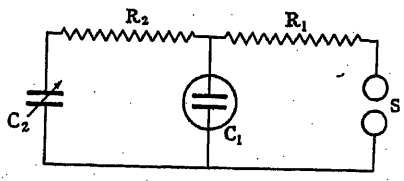


FIG. F.

be made to remove the beam to the initial position O without blackening the exposed film, before a further record can be made. Many arrangements have been used to suit different experimental conditions, as the author points out. The first rapid jump Ox_1 may be obtained by the sudden charge or discharge of a special pair of timing plates through a circuit of very small time-constant. This operation may be initiated simultaneously with the normal time deflection through a spark-gap common to the two circuits. An arrangement due to Krug* avoids the necessity for a special pair of timing plates to produce the initial motion of the beam and bring it on to the photographic plate. The arrangement is shown in Fig. F, in which C_2 represents a variable condenser, C_1 the time deflection plates

* *Elektrotechnische Zeitschrift*, 1930, vol. 51, p. 605.

of the oscillograph, R_2 and R_1 resistances, and S a spark-gap. A d.c. supply is connected across the spark-gap. When the gap breaks down, the voltage on C_2 falls to a value $VR_1/(R_2 + R_1)$, V being the trigger voltage, in a time given approximately by $C_1 R_1 R_2/(R_1 + R_2)$, where C_1 represents the capacitance of the timing plates. The subsequent abscissal motion is controlled by the time-constant $C_2 (R_1 + R_2)$, where C_2 is the capacitance of the variable condenser. By using a charging voltage instead of a discharging voltage to deflect the beam, the final position of the latter can be made to coincide with the initial. There then arises the problem of synchronizing this deflection with the ordinate deflection due to the phenomenon under investigation. When the latter is controlled and its voltage is the same as that which operates the timing circuit, the two can be released by a common spark-gap. Further control can be exercised by varying the length of the conductor connected to any one pair of plates. Generally the ordinate voltage differs from the value used to operate the timing plates. In such a case it suffices to allow the spark-gap which releases the time sweep to be placed near a gap which is released by the transient, so that when the latter breaks down the former is disturbed and breaks down also. This modification is readily adapted for registering uncontrolled transients such as those occurring on transmission lines, as well as the controlled transients of the laboratory. The voltage divider presents a special problem in high-voltage cathode-ray oscillography owing to the very high speeds frequently involved, with a consequent tendency to distortion and delay. I should like to refer to two points in this connection. The oscillograph cannot always be placed close to the test object or transmission line, and consequently a long lead or cable may be required to join the high-voltage arm of the divider to the low-voltage end across which the ordinate plates are connected. If such a divider is to divide the voltage correctly and without distortion, no reflection of the fraction of the surge which travels along the connecting cable must occur at the low-voltage end of the divider. To ensure this, the equivalent surge impedance must form part of the low-voltage arm of the divider. Such a divider has been used and described by Gabor.* For use on transmission lines carrying the working voltage at power frequencies the divider can be made insensitive to low frequencies. A considerable quantity of literature has accumulated in Europe and America on the subject of the recording of high-speed transient phenomena. Dr. Wood's paper is welcome as showing that in this country the importance of such developments is not being overlooked.

Dr. J. L. Miller (*communicated*): We have recently developed a cold-cathode type of oscillograph for the measurement of high-speed transients, and some remarks based on our experience may be of interest. Except in the Introduction, Dr. Wood's paper makes little mention of cold-cathode discharge tubes, despite the fact that most of the transient measurements by the General Electric Co. and the Westinghouse Co. in the United States, Norinder in Sweden, and Berger in Switzerland, have been made with high-voltage cold-cathode type instruments. Obviously, therefore, these instruments form quite a large and important section of the subject of cathode-ray oscillography. We found it a troublesome matter to build a discharge tube that would operate quietly at 60 000 volts for long periods, would have the inherent property of giving a finely-focused cathode ray, and would not cause pitting of the cathode surface after too short a time. Quite a lot of experimenting had to be carried out before the laws governing the design were understood. It is obvious that the diameter of the beam can be controlled by the size and shape of the cathode and of the discharge tube round and behind the cathode, and we made considerable efforts to use these data so as to provide good electrostatic pre-anode focusing. In addition, of course, main electromagnetic focusing takes place some distance below the anode. The necessity of good pre-anode focusing is sometimes questioned, but obviously it is essential in some form or other, and all cold-cathode instruments have it by accident if not by design. The only real question is: How good should this focusing be? Our experience is that from the point of view of fineness of trace on the photographic plate it is better to use good pre-anode focusing and a small anode hole, rather than poor focusing and a larger anode hole. Thus, although it would appear from the few details given from time to time in the foreign technical Press that some designers do not particularly concern themselves with this question, it is worthy of note that many of them do. For instance, Rogowski is the great advocate of pre-anode electromagnetic focusing, and he uses a concentrating coil above the anode; Knoll designs his later discharge tubes so that the cathode and anode are very near together, and, in addition, the cathode is surrounded by an anode tube; and Binder obtains very good electrostatic focusing by surrounding the cathode with a metal cylinder which is free to take up any potential. Berger tells me that his cathode is surrounded by two or three concentric glass cylinders of gradually increasing length. It is also possible to obtain quite good focusing by means of a cylindrical glass shield whose periphery is just below that of the cathode; in addition, a suitably shaped hollow cathode can be used. Another question which frequently arises is whether it is better to have a glass or a metal discharge tube. When a glass tube has been in operation for some time, a layer of metal may be deposited on the inner surface of the glass due to the pulverization of the cathode. Even when this deposit became excessive due to an accident, it could not be ascertained that it had any detrimental effect, and this view is confirmed by Dicks.* We can therefore state that the glass discharge tube has a useful life of many hundreds of hours, all that is required being a periodic renewal of the cathode. The metal tube is better for mechanical reasons because it lends itself more easily to accurate centering, and because it is more readily adaptable to the use of devices giving still better electrostatic focusing. Regarding photographic films or plates, high-voltage rays will record photographically on almost any emulsion when inside or direct photography is used, but it is quite a

* "Forschungshefte der Studiengesellschaft für Höchspannungsanlagen" (Vol. 1 of the Research Organization for the Study of High-Voltage Problems).

* H. Dicks: "Glass or Metal Discharge Tubes?" *Archiv für Elektrotechnik*, 1931, vol. 25, p. 523.

different matter when it is desired to employ external direct contact photography by utilizing the luminosity effect of cathode rays falling on a phosphorescent material like calcium tungstate. In all our earlier work inside photography was employed, but for the sake of convenience and ease of operation we decided to explore the possibilities of outside photography. Using an ordinary commercial plate, an excellent record of an oscillation having a frequency of 200 000 and superimposed oscillations of 10^7 cycles per sec. on one part of it, could be obtained with one single sweep of the time base, the cathode potential being 60 000 volts. Using external photography and a similar photographic plate in direct contact with the glass sheet 0·25 mm thick, coated with calcium tungstate and supported by a suitable grid, the main oscillation was easily discernible on developing, but the superimposed oscillation was very difficult to follow. Rogowski's external records show a similar fault at very high frequencies. In order to get good records of higher frequencies with outside light blackening photography, it seems that one must employ the minimum thickness of glass to prevent blurring, and have rather more current in the post-anode beam than is necessary for internal photography. Eventually, when the cathode potential becomes high enough, the glass will transmit a reasonable percentage of the electrons striking it, and I am interested to see that the author estimates that at 160 kV, using glass 0·17 mm thick, there would be a 50 per cent transmission. A further difficulty with external glass contact-photography lies in the fogging produced on the photographic plate when records are taken at short time-intervals, because the fluorescent material is liable to emit light for some considerable time after the ray has been removed from it. Although our development work in this direction is not yet complete, at this stage we agree with the author that the direct effect is many times greater than the indirect effect. Probably, if the inconvenience of breaking the vacuum in order to change plates is to be avoided, it may be necessary to use a real Lenard window employing thin aluminium sheet for recording very high frequencies. In his remarks on the timing of single impulses, the author draws attention to the ingenuity and skill required to synchronize the unknown transient and the timing or sweeping movement. Actually, the problem is a little more difficult than that indicated by his statement, because with the notable exception of the Norinder instrument all oscillographs require the synchronization not of two, but of three circuits, the additional one being the ray-withdrawing circuit. This operates in such a way that the beam is prevented from passing through a small hole in a diaphragm in the upper part of the oscillograph by means of a potential applied to one pair of deflecting plates. Closure of a switch automatically destroys this potential, allowing the beam to pass through the hole in the diaphragm; after a very short time-interval, variation of the potential on the second pair of deflecting plates causes sweeping to commence, and then, after a predetermined delay, the unknown transient arrives at the third pair of deflecting plates via a short line or delaying cable. When the beam has completed its traverse, the potential is re-applied to the first pair of plates and the beam is withdrawn. The whole operation may be over in something of the order of a few micro-seconds, and we have successfully used the arrangement to record artificial transients having a total length of $1{\cdot}7 \times 10^{-6}$ sec. Some experimenters are in favour of employing in the withdrawing circuit a valve the grid potential of which can be controlled by the surge current flowing in the timing circuit, so that withdrawal of the ray cannot occur until the current in the timing circuit has fallen to a predetermined value, thus causing the ray to be withdrawn automatically at the end of its traverse. It is our experience, however, that it is difficult to overcome the capacitance effects to earth of the supply transformer for the valve. We find it preferable, therefore, to use a connection where the withdrawing circuit is directly in parallel with the timing circuit; if care be taken in the choice of capacitances, damping resistances, and resistances to absorb reflections, this connection is capable of giving very satisfactory operation. Time bases which sweep across in, say, 1 micro-second or less, are liable to grave errors unless due precautions are taken, and occasionally one has the unhappy experience of finding that time is going backwards! Also, the damping in the circuits in which the transients under examination exist, must not be overdone. The author describes a mechanical switch of a very simple type which he has used to good effect. We have used an even simpler one which consisted of a large mousetrap with just one or two additions, and it worked very well! I am glad to see that the author draws attention to the fact that resistance-type potentiometers are liable to give rise to distortion when used for high-speed work. I support this view, and think that their use is to be deprecated. I should also be glad to know his opinion of the insulator-string-type potentiometer.

THE AUTHORS' REPLIES TO THE DISCUSSION ON THEIR PAPERS (SEE PAGES 41 AND 57 RESPECTIVELY).

Dr. A. B. Wood (*in reply*): The enthusiastic discussion is a sufficient indication of the increasing interest which is being taken in the development of cathode-ray oscillographs. Such a response is very encouraging to those taking an active part in this development. I am particularly grateful to Dr. Allibone, Mr. Davis, and Dr. Miller, for their remarks on high-voltage oscillographs used to record transients at very high speeds. Little work of this character has hitherto been reported in this country, and I was therefore forced to refer somewhat extensively in my paper to the results obtained by Continental and American workers. As shortage of space prevents me from replying adequately to all the speakers, I must ask their indulgence if I have overlooked any of the points they have raised.

Dr. Drysdale refers to a few of the desirable features of cathode-ray oscillographs and mentions in particular sealed tubes with external photography. I have indi-

cated in the paper how far these desiderata have been achieved up to the present, but there is still much to be done. The two traces obtained on one plate were not made simultaneously by two independent cathode streams. They were made independently with a single stream of cathode rays. Dufour describes a double tube for such a purpose, but I do not know whether it has proved successful.

Replying to Dr. Simeon, ordinary gelatine plates are sufficient for many purposes, depending on the recording speed and the generating voltage of the cathode rays. At low recording speeds, low-voltage cathode rays will record on ordinary plates. Cathode rays generated at high voltages (30 kV or more) will record sufficiently well on ordinary plates at the highest speeds of traverse. The silver iodide plates which I have used are not difficult to make; they are similar in many respects to Schumann plates and may be prepared in somewhat the same manner.

Dr. Allibone and I are working at opposite ends of the cathode-ray "scale." He requires the maximum recording speed irrespective of voltage sensitivity, whereas I want both voltage sensitivity and high recording speed. As I have pointed out in the paper, these two desiderata are not easy to obtain simultaneously. The "lens action" of the solenoid is very interesting, and my statement in this connection refers to a long solenoid with a magnetic field which is assumed to be uniform. The focusing action to which Dr. Allibone refers is apparently due to the radial component of a distorted field produced by a short solenoid.

I would draw Mr. Herd's attention to my remarks at the beginning of the paper, explaining that the division of cathode-ray oscillographs into two groups—high- and low-voltage—is purely arbitrary. It is impossible to draw satisfactory lines of voltage division to distinguish between the various types. While opinions seem to vary with regard to the use of the words "phosphorescence" and "fluorescence" in connection with a material like calcium tungstate or willemite, I think Mr. Herd has got hold of the less popular definitions. The name "fluorescence" is generally applied to the phenomenon exhibited by such substances as fluorescene (an aniline derivative), paraffin oil, and a solution of quinine sulphate, which when illuminated by violet or ultra-violet light emit green or blue light (of longer wavelength than the incident light). Fluorescene emits a brilliant yellowish-green light when exposed to daylight or an arc. The phenomenon of fluorescence was investigated by Sir George Stokes, who framed the law relating to the degradation of wavelength. Fluorescence continues only so long as light is incident on the fluorescent substance. Certain substances, e.g. the sulphides of calcium, barium, and strontium, continue to emit light, however, when the existing source of light is removed. This effect is termed "phosphorescence." Balmain's luminous paint contains a mixture of these sulphides. Calcium tungstate, willemite, etc., also exhibit phosphorescence. The effect may continue for a period varying from 10^{-4} second to several hours, depending on the nature of the substance. Glass is phosphorescent under the action of cathode rays. All solid fluorescent substances are found to be phosphorescent also, and it may be due to this fact that confusion has arisen. Both phenomena are quite distinct, of course, from the faint greenish-white luminosity which phosphorus shows when exposed to moist air in the dark. This effect is due to chemical oxidation (slow combustion) of the phosphorus. I am obliged to Mr. Herd for details of the simple arrangement using a condenser and diode which he has devised, and for the reference to A. L. Samuel's paper on a new time-base.

Mr. Whipple raises the important point that in view of the large variety of cathode-ray oscillographs it would be an advantage if some common basis of comparison (e.g. a figure of merit) could be devised. The principal difficulty which would be encountered in formulating such a standard arises from the fact that the "merit" of an oscillograph depends upon the object in view. Thus Dr. Allibone requires a high recording speed and is not in the least concerned with voltage sensitivity. I, on the other hand, regard this as very important. There is no common ground of comparison in these two cases. The matter is, however, sufficiently interesting and important to warrant further consideration.

In reply to Prof. MacGregor-Morris, I cannot venture an opinion regarding the difference in the focusing action of the gas in the Standard Telephones and Cables tube and the von Ardenne type. In both cases gas is used to produce the focusing action. There must be other ways of focusing which do not involve the objectionable features associated with the introduction of gas into the tube. As to the high luminous efficiency of the phosphorescent screen of Rogowski and Ruhlemann, while the result is very striking one cannot imagine any known phosphorescent material withstanding such a bombardment for more than a few minutes. With regard to the mercury switch, I have not experienced such troubles as those to which Prof. MacGregor-Morris refers.

Prof. J. T. MacGregor-Morris and **Mr. H. Wright** (*in reply*): Although the higher-voltage hard-vacuum tubes are rapidly developing in the direction of higher recording speeds and so are finding new fields of application as well as extending the older ones, we feel that the lower-voltage tube has a field of at least equal breadth and freshness. The sealed-off tube is an instrument easy to handle and can be set up almost anywhere in a laboratory in a short time, costs little in time or money for maintenance, and is ready for use as soon as the circuit is complete. Until the hard tube can be handled in this way the sealed-off gas-focused tube will continue to hold sway in its own wide province in spite of the errors and possible troubles due to the presence of the gas.

Dr. Drysdale suggests that the most promising direction for development is the production of better fluorescent materials for the screen. Hitherto efforts have been made to obtain screens giving light which is brilliant for visual work and actinically active for photographic work. It is now possible to obtain photographic plates which are many times more sensitive to yellow light than any other plate is to light of wavelength extending from the blue to the ultra-violet region. Were it possible to produce a fluorescent material giving a yellowish or faintly green light there would be no

need to use quartz either in the tube or in the camera lens.

The almost simultaneous recording of current, voltage, and time-base was regularly carried out for over a year at East London College. The records were made at power frequency by means of a commutator arrangement which successively put each trace on for one cycle. In many phenomena under investigation the change occurring over three cycles is very small, so that in these cases this method can be applied. It may be noted here that time intervals down to 10 micro-seconds could be measured on photographic traces obtained with this apparatus, and the measurement of shorter times would have been possible had the phenomena under investigation been sufficiently constant to allow of longer exposure.

Mr. Calthrop has developed a formula which certainly gives a good approximation, but we cannot agree with him that the asymmetry of the deflection/voltage curve is due to experimental error. As the plate-current curve is not symmetrical and the space-charge effect will be closely related to this current, it is only reasonable to suppose that the space charge will be different when the plate is positive to that which it is when negative. Unfortunately, the equations given by Mr. Calthrop do not hold at the lower voltages. It does not seem likely, in view of the complicated nature of the current, that any simple equation can be obtained which will fit the curve at all working values of the voltage. The difference is probably due to the asymmetrical arrangement of the deflecting plate circuit, as one plate is connected permanently to the anode and the other is either at a higher or lower potential. This can be overcome by arranging the plates in "push-pull" as has been suggested, but this would not be possible with a tube of the Standard Telephones Co.'s pattern. It is not out of place to remark here that there is a difference of opinion regarding the exact manifestation of the threshold effect. Johnson states that there is no deflection for the first few volts, while Bedell and Kuhn depict the deflection as being produced in steps over about the same range of voltage. In the work under discussion the effect has always been observed as a continuous one, as the curves show.

It is pleasing to note Mr. Herd's remarks, which so strikingly show the possibilities of recording with the sealed-off gas-focused tube. Now that so much interest is being taken in this type of tube, as is borne out by the comparatively large number of new types which have been put on the market recently, it is to be hoped that still further developments will be forthcoming to make recording more easy. The potentiometer method of detecting the "origin distortion," as Mr. Herd suggests calling it, would lead one to the conclusion, from considerations of the actual results obtained, that the distortion disappears entirely at certain conditions of focusing. The sensitivity of one pair of plates is different from that of the other, and the distortion effect is also different. The distortion which is observed can only be the difference in the distortion produced by the mutually perpendicular deflecting pairs, so that, due to their different distances from the screen, there are likely to be a large number of combinations of filament current and anode voltage which makes the distortion/sensitivity ratio the same for both pairs of plates, and so the trace appears undistorted although the threshold effect is still present, and may even be increased and not diminished. With regard to the best name to use for this effect, there are four terms which are used by different experimenters:—(1) The threshold effect, (2) space-charge effect, (3) zero-point anomaly, and (4) origin distortion. Of these the space-charge effect is the only one which suggests a possible cause. For the present, however, until the effect is completely understood it is probably wiser to use the term "origin distortion."

We agree with Mr. Whipple that a factor of merit for tubes would be a highly desirable thing to have. At the moment, nothing can be suggested, other than his proposal, which would afford a true comparison. The one drawback associated with any method involving relative photographic sensitivities is that the actinic light from the fluorescent screen is concentrated in certain parts of the spectrum. This would mean that the specification of a given plate as a standard might conceivably penalize one tube because its fluorescence was green and not blue, whilst if another plate were used it might completely reverse the results. Another point which would have to be taken into account would be the fineness of the trace, as a thick one could lead to fairly large errors in measurement.

The trouble with the blurred spot and parasitic looping described by Mr. Mines has also been experienced by us. In our case we found it to be due to insufficient smoothing of the anode supply. In the presence of an external field this will cause the beam to oscillate slightly, owing to the change in sensitivity with anode voltage, and this produces the blur. When the tube is used under certain conditions this oscillation becomes "locked" with either the time-base or the applied oscillatory deflecting force, and appears as a steady figure on the screen.

We should be interested to hear of experiments embodying Dr. Wood's suggestion of the focusing wire. Would not the trouble be that, due to the comparatively long time it takes for the electrons to travel from end to end of the tube, the repulsive force between the electrons in the stream would have time to make itself evident by lack of focus? The reason that the term "gas-filled" did not appear in the title was because it was felt that the term had been so long associated with the half-watt lamp that it implied a high gas pressure instead of a fairly good vacuum. We suggest that the term "gas-focused tubes" might be used as being nearer the mark, and we have now altered the title of the paper.

Mr. Bedford's contribution to the discussion has certainly gone a long way towards explaining the mechanism of origin distortion. He rightly states that the means of ridding the screen of its negative charge has too long been overlooked. On analysing the curves shown in Fig. 17, i.e. those for the plate current in the 4018A tube, it was found that they had the general form

$$I = A + BV^n + C \operatorname{arc\,sinh} DV$$

the values of the constants varying for each curve, and it is interesting to note that this falls in line with Mr. Bedford's analysis. It would seem that the term A

represents the normal drift of electrons returning from the screen to the anode, and the last term shows how these redistribute themselves between the two plates as the potential difference between the plates is increased, the total number arriving at the plates being constant. The exact significance of the middle term is not too clear, as it gives positive values of current for negative values of voltage, although the form of it is somewhat as would be expected for a diode, corresponding to the current produced by the removal of ions from the beam.

The remarks of speakers have definitely indicated the direction in which improvements in this type of tube are desired, and they are, in brief, speedier recording and the elimination of origin distortion. With the wider interest and augmented experience of increased usage, it is to be hoped that these improvements will not long be delayed.

A CIRCULAR TIME-BASE GIVING RADIAL DEFLECTIONS, FOR USE WITH THE CATHODE-RAY OSCILLOGRAPH.*

By The Staff of the Radio Research Station, Slough.

(*Paper first received 25th February, and in final form 18th April*, 1932.)

Summary.

In the study of electromotive forces varying with time, the electromotive force under examination is caused to modulate similarly and simultaneously two voltages which are applied in quadrature to the deflecting plates of a cathode-ray oscillograph. The resultant screen-image on the oscillograph consists of a circular time-base, on which are superposed radial deflections delineating the wave-form and the time relationships of the applied electromotive forces.

Introduction.

Perhaps the most frequent of all the applications of the cathode-ray oscillograph in experimental research is in the study of the variation of an electromotive force with respect to time. The electromotive force may be in itself the primary object of study, or it may be derived from electrical or mechanical phenomena which may conveniently be converted into a proportionate electromotive force. The use of a piezo-electric crystal in association with a cathode-ray oscillograph for the study of pressures may be cited as an example of investigations of this latter class. Now that sealed-off cathode-ray oscillographs can be obtained in a comparatively inexpensive and reliable form, it may reasonably be hoped that this remarkably flexible tool will find applications in still wider fields of investigation. The purpose of the present paper is to describe a convenient accessory circuit for use in such applications.

Linear Time-Bases.

In the earlier applications of the cathode-ray oscillograph to the study of varying electromotive forces, it has been customary to trace out the time curve of variation in Cartesian co-ordinates, the ordinates being proportional to the electromotive force under investigation, and the abscissæ being made to vary in accordance with a known and controlled function of time by means of special time-base circuits. The inconvenience of the sinusoidal time-base has been avoided by the introduction of a variety of linear time-bases, in which the indicating spot is made to move at a substantially uniform velocity from left to right, and then to return quickly to the left. This form of time-base is produced by the application to the time-base electrodes of an electromotive force of " saw tooth " wave-form. One such linear time-base† derives the required electromotive force from the fluctuations of the potential of the grid of an intermittently oscillating (" squegging ") valve using a saturated diode as the grid leak. This device, originally introduced for the study of the wave-form of atmospherics, has recently been used for the study of the retardation time of echo signals returned from the ionized layers of the upper atmosphere.‡

Circular Time-Bases.

In some investigations it may be convenient to delineate time relationships in polar co-ordinates instead of in Cartesian co-ordinates. Even when polar co-ordinates are not required, it may be convenient to refer the electromotive forces under study to a time-base of circular form rather than to one of linear form. An example of such an application is found in the harmonic comparison of frequencies.§

In previous applications of the circular time-base with truly radial reflections, the deflectional sensitivity of the oscillograph has been modulated in accordance with the variations of the electromotive force under investigation, by applying this electromotive force in series with the

e Papers Committee invite written communications, for consideration view to publication, on papers published in the *Journal* without being : a meeting. Communications (except those from abroad) should reach cretary of the Institution not later than one month after publication of er to which they relate.

† E. V. Appleton, R. A. W. Watt, and J. F. Herd: *Proceedings of the Royal Society*, A, 1926, vol. 111, p. 672.

‡ E. V. Appleton: *Nature*, 1931, vol. 127, p. 970.

§ D. W. Dye: " Improved Cathode Ray Tube Method for the Harmonic Comparison of Frequencies," *Proceedings of the Physical Society of London*, 1925, vol. 37, p. 158.

anode battery.* If, however, the electromotive force to be studied varies rapidly, this method is unsatisfactory when used with cathode-ray oscillographs of the sealed-off variety, in which the residual gas pressure is relatively high. The changes in the effective anode voltage which result from the modulation process alter the sharpness of focus of the indicating spot, since such sharpness is a function of the filament current, the anode voltage, and the gas pressure.

In experiments on the retardation time of wireless echoes, Goubau and Zenneck† utilized a circular time-base obtained by applying equal timing voltages in quadrature to the two pairs of deflecting plates in the oscillograph. The electromotive force under observation was superposed on the electromotive force applied to one pair of plates, thus producing vertical departures from the circular time-base. If the echo signal arrived when the indicating spot was moving with a considerable horizontal component of velocity, its time of incidence was easily determined, but if it arrived when the spot was moving nearly vertically, the departure from the circle was nearly tangential and the order of accuracy of the determination of time of arrival was relatively low.

In an editorial comment‡ on these experiments, it was suggested that the experimental technique might be very greatly improved by the use of a radial instead of a vertical movement of the spot. The particular electrode system suggested in the editorial note would not, however, give the desired result. Circuits had previously been devised in this station for fulfilling these requirements, and it is thought that an outline of the method may be of value to other workers.

Description of the New Device.

If the electromotive force under observation is represented by $e = f(t)$, it is desired that the spot should move on a curve of which the polar co-ordinates are

$$r = a + b\,.f(t) \quad \text{and} \quad \theta = \omega t$$

where a and b are constants and ω is the angular velocity of the spot in radians per second.

The cycle of indication will be repeated $f\,[= \omega/(2\pi)]$ times per second.

Changing to Cartesian co-ordinates, we have

$$x = r\cos\theta = [a + b\,.f(t)]\cos\omega t$$
$$y = r\sin\theta = [a + b\,.f(t)]\sin\omega t$$

It will be seen that the desired result is obtained by applying to the plates voltages in quadrature, these being modulated by the electromotive force under observation.

Of the many modulating methods available the push-pull modulator described§ by Heising was chosen.

The voltages in quadrature are obtained by tapping off the voltages from a condenser and a resistance in series. The circuit, which is shown in Fig. 1, is nearly self-explanatory. C and R are adjusted to have the same impedance at the frequency f, and they supply two audio-frequency transformers with centre-tapped secondaries. Condensers C_1 are connected across the half secondaries, in order to provide a low-impedance path for the transient $e = f(t)$ which is applied between the centre points of the secondaries and the valve filaments. The anodes of the valves are connected to

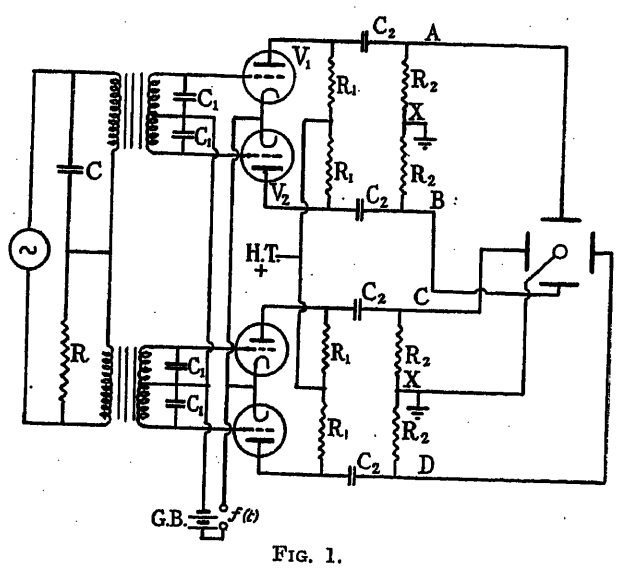


Fig. 1.

H.T. + through resistances R_1 and (through condensers C_2) to the four deflecting plates. (In the cathode-ray oscillograph employed, the four plates are separately accessible. This avoids the use of an output transformer with centre-tapped primary, which would probably distort high-frequency transients.)

The grids of the valves are biased so that the operating

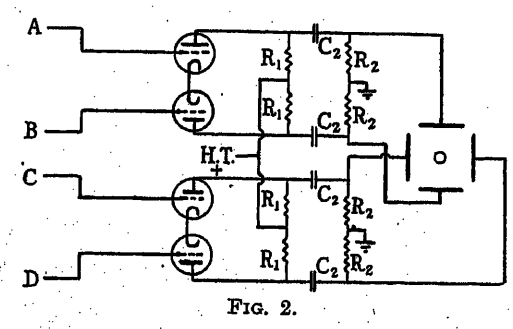


Fig. 2.

portion of the $i_a - e_g$ characteristics is approximately parabolic.

The theory of this modulator is given in Appendix 1.

Use of the New Base.

The use of the device may be illustrated by Figs. 3 and 4. In these the electromotive force $e = f(t)$, represented approximately in Cartesian co-ordinates in Fig. 3, was supplied from an intermittent (" squegging ") oscillator, the grid condenser discharging through an ohmic resistance. The variation of the time-constant of the condenser and its associated leak controls the

* N. V. Kipping: *Electrical Communication*, 1924, vol. 111, p. 71; also in E. B. Moullin's "Radio Frequency Measurements," 2nd edn., p. 211.
† *Zeitschrift für Hochfrequenztechnik*, 1931, vol. 37, p. 207.
‡ *Wireless Engineer*, 1931, vol. 8, p. 463. (Formerly *Experimental Wireless and Wireless Engineer*.)
§ *Proceedings of the Institute of Radio Engineers*, 1925, vol. 13, p. 296. This contains a very complete summary of the modulation products obtained.

period of operation over a wide range. Fig. 4 is reproduced from a tracing of photographs taken with the intermittent oscillator working at 50, 100, 200, and 650 cycles per second. In each case a separate exposure was given in order to show the undisturbed circular base. It will be seen from Fig. 4 that the straight part of the trace, representing the extremely rapid charging of the condenser during high-frequency oscillation, is approximately radial, no matter at what point in the cycle it occurs.

Advantages.

The advantages presented by the time-base circuits just outlined include the following.

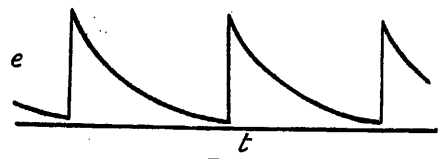


Fig. 3.

In common with other circular time-base circuits the length of base can be made nearly as great as the effective circumference of the oscillograph screen—in the present case 31 cm.

The circular time-base, by reason of the continuous angular rotation of the spot, lends itself well to permanent and accurate calibration as regards time; for example, by the application of a voltage of frequency nf in series with the voltage e. In these circumstances stationary ripples will appear on the circular base, dividing it into n parts representative of equal intervals of time. This subdivision is independent of the small departures from truly circular form which may result from imperfections in the oscillograph.

The circuits described eliminate the defects of focusing experienced with other circuits in which radial deflections are obtained.

Applications.

Among the many types of experiment in which the application of this form of time-base would be advantageous, a few typical cases may be mentioned.

It is unnecessary to add to what has already been said on the direct application of the circuits described in the study of the variation with time of transient phenomena, whether these occur periodically or not. It may, however, be useful to refer to other typical applications in which the circuits have special merit.

In the harmonic comparison of frequencies, for example, the methods described by Dye and others may be applied over a considerably extended range. The uniform sharpness of the spot over the whole trace enables comparisons to be made between the reference frequency of the time-base and a very high-order multiple of that frequency. Observations have been made on about 18 000 cycles per second against a time-base of 50 cycles per second. In this case the ripples are separated by one degree of arc which, on the circumference of 31 cm used in the experiment, corresponded to a distance of 0·8 mm, and the latter is sufficiently large compared with the effective diameter of the indicating spot to leave no ambiguity in the determination.

The circuits also lend themselves to the accurate comparison of two frequencies of very different orders when these frequencies are not in an exact harmonic relation. If the frequency f_1 is much greater than f_2, f_1 is applied as the time-base frequency while f_2 is caused to apply a short transient electromotive force. If f_1 is an exact multiple of f_2 the transient will appear always at the same point on the screen, while departures from the exact relation will result in displacements of the transient in the screen image. For example, if f_1 is made accurately 50 cycles per second and f_2 is derived from the alternate swings of a seconds pendulum, the apparent movement of the transient on the screen will show the departure of the pendulum frequency from uniformity. Since a movement of 1° of arc can easily be detected, a departure of $1/50 \times 1/360 = 1/18\,000$ sec., i.e. 1/36 000 (about 0·003 per cent) of the period, in the rate of the pendulum can be measured with ease. This departure corresponds to a rate of about $2\frac{1}{2}$ seconds per day, and the determination is made in a few seconds if the swings of the pendulum are themselves uniform. The details of any non-uniformity in swing can be quickly studied in the same way.

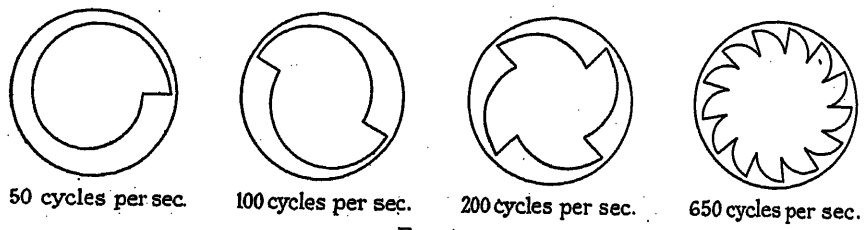


Fig. 4.

Thanks are due to the Department of Scientific and Industrial Research for permission to publish the details of this device.

APPENDIX 1.

The Theory of the Modulator.

It is assumed that the valve is working over a part of the characteristic which is parabolic, i.e. that the relation between i_a and e_g is of the form

$$i_a = c + de_g + he_g^2$$

where c, d, and h are constants.

It is only necessary to consider the upper half of Fig. 1.

The voltage applied to the grid of V_1 is

$$a \cos \omega t + b \,.f(t)$$

That applied to the grid of V_2 is

$$- a \cos \omega t + b \,.f(t)$$

The voltage across the resistance R_1 connected to V_1 is

$$R_1 i_a = R_1\left[c + d\left\{a \cos \omega t + b \,.f(t)\right\} + h\left\{a \cos \omega t + b \,.f(t)\right\}^2\right]$$

and in the case of V_2 is

$$R_1\left[c + d\left\{- a \cos \omega t + b \,.f(t)\right\} + h\left\{- a \cos \omega t + b \,.f(t)\right\}^2\right]$$

The resultant deflection on the "vertical" plates, due to the difference between these two, is therefore proportional to

$$R_1\left\{d(2a) \cos \omega t + h(4ab) \cos \omega t \,.f(t)\right\}$$

by expanding and subtracting term by term, and this is equal to

$$2aR_1 \cos \omega t\left[d + 2bh \,.f(t)\right]$$

which is of the form required.

APPENDIX 2.

Components for a 50-Frequency Time-Base.

The following values of components were used (in conjunction with a 50-frequency supply) in the time-base arrangements for a cathode-ray oscillograph with a deflectional sensitivity of about 1 mm per volt.

The valves should be matched; and this is best done by turning off the circular-base electromotive force and applying only the transient to be studied. When the circuit is balanced the spot should remain stationary, i.e. no trace of the transient should be detected.

The values of the components used were:—

$f = 50$ cycles per second; voltage, about 1·5 volts;
$C = 4\mu$F; $R = 800$ ohms; $C_1 = 0{\cdot}04\mu$F;
$C_2 = 0{\cdot}25\mu$F.
Low-frequency transformers, ratio 1 : 3·5.
Valves, L.S.5b, working with 4 volts L.T.
$R_1 = 50\,000$ ohms; $R_2 = 1$ megohm;
H.T = 180 volts; grid bias = 4·5 volts.

If greater amplification than that given in Fig. 1 is required, the leads are broken at A, B, C, D, and are connected as shown in Fig. 2, the points X in Fig. 1 being connected to a bias battery of about 6 volts.

DISCUSSION ON

"THE DESIGN OF A DISTRIBUTION SYSTEM IN A RURAL AREA."*

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, GLOUCESTER, GLASGOW, SHEFFIELD, NEWCASTLE, MANCHESTER, LIVERPOOL, AND BIRMINGHAM (SEE VOL. 70, PAGES 235 AND 449).

Messrs. E. W. Dickinson and **H. W. Grimmitt** (*in reply*): In the first place we wish to express our appreciation of the way in which the paper has been received and to thank those who took part in the discussion for the constructive criticism which indeed was what it was desired to evoke, because the subject is admittedly a most thorny one. We had little idea that the paper would arouse such widespread interest and discussion, but it was clear from the first meeting that this was because the matter had been engaging the earnest attention of so many in the industry. We ourselves had considered that the paper was little more than a collection and a digest of information.

We are pleased to find that the main conclusions of the paper have not been materially affected by the discussion. It has been so great in volume—upwards of 70 speakers have taken part—that it is obviously impracticable to reply to each speaker individually, nor is it desirable, as with discussion at so many Centres the same point has been raised repeatedly. Hence we propose to answer points rather than speakers. We ask indulgence if any points have been overlooked.

Some important parts of the paper escaped discussion altogether, and it may therefore be inferred that these were generally accepted. Much of the discussion was devoted to detail of design and reduction in cost of construction, especially of the low-tension distribution. The question as to a proper form of tariff again evoked much interest, and we have been somewhat criticized for not carrying the matter further. We intentionally refrained from doing so, being fully convinced that a matter so highly controversial should not be introduced as though it were a subsidiary one, and contented ourselves with expressing the opinion, which we would reiterate very strongly, that a two-part tariff wherein the service charge rises and the unit charge falls with increased use is essential (see page 235). The subject is more fully dealt with later in our reply, but we would seize this opportunity to suggest that the subject of tariffs is one that might well be dealt with comprehensively by some member better qualified than ourselves and having more intimate knowledge of the problem. At any rate the conclusion reached in the discussion was generally to approve of the unit charge being kept in as close a relationship as possible with actual running cost. Although a great variety of opinion was evident as to what the basis of the "Service charge" (based on the fixed costs) should be, it seems clear that the industry is still seeking for a method of charging which bears some closer relationship to the quantities sold, namely, kilowatts and kilowatt-hours, than has so far been the custom. If electricity is to become a commodity of universal use its sale price should not, for instance, be made mysterious by a reference to amenities of a certain district or the ability of the consumer to pay what might be inferred from the use of rateable value as a basis. The basis of floor area is for the same reasons incorrect as only a portion of a dwelling may be occupied.

Several speakers emphasized what we said as to the importance of keeping down fresh capital expenditure to a minimum and the necessity of making better use of the capital already invested in order to afford progressively cheaper supplies to consumers.

On the question of costs of equipment as shown in the schedules on pages 226, 230, and 232 and adopted in the paper, opinion seems to be divided, some considering the estimates much too low, while others found them too high. We conclude, therefore, that the figures we have taken may be regarded as a fair average throughout. Since writing the paper we have been confirmed in our belief by the fact that large contracts have been placed at prices approximately equal to, if not less than, those given in the paper.

As was to be expected, the paper was approached by some speakers from the point of view of their own undertakings, or of their own particular experiences, and their criticism went to show how local physical conditions affect detailed design.

Modifications of Conclusions.

Referring to the conclusions set out on page 234, it can be said that no exception was taken to the accuracy of the statistics and the deductions therefrom, on which the earlier part (Conclusions 1 to 5) was based.

Nothing was advanced to rebut the conclusion that the present radius of supply of electricity can be extended materially so as to include areas of less population density than at present provided for—roughly 375 persons per square mile at the time the paper was written (Table 6)—and that this can be done with confidence.

No argument has been adduced to show that Conclusion (7)—that in rural areas any reduction in the charge per unit to consumers will lead to increased sales and greater gross revenue—is untrue.

As regards Conclusion (8), we admit that "application of a tariff under which the charge for electricity is reduced *pro rata* to consumption, it can confidently be hoped to tap large sources of revenue" is rather a bald statement and should be modified as it is applicable to domestic supplies, for which load factor can roughly be

* Paper by Messrs. E. W. Dickinson and H. W. Grimmitt (see vol. 70, page 189).

gauged. For power purposes the price should be a matter of agreement based on a kilowatt and unit charge, if possible modified for off-peak load supplies.

In regard to Conclusion (9) the discussion has not led us to depart from the view that development should take place on a comprehensive design and not sporadically (see page 191). Much that was cogent was advanced in the discussion in favour of a creeping development outward on a flexibly designed network, always giving time for revenue to accrue to justify further expansion. We are satisfied, however, that the comprehensive design will be more and more adopted as time goes on, and we merely cite, as the most recent examples, those for Dumfriesshire and Northern Ireland.

As to the extent of the area that should be considered, we quite realize that areas of much smaller extent than 400 square miles exist, but it seems obvious that they should be amalgamated with neighbouring areas.

Conclusion (10)—that the best pressure for the distribution in rural work with scattered loading is 11 000 volts, 3-phase—has been generally conceded, and is desirable both from the point of view of uniformity and of interchange between areas. As to the system of supply, we recognize that a case has been made out for single-phase working in those areas where there is little hope of industrial loads or where the load is purely domestic.

Conclusion (11)—that the cost of overhead lines and equipment can be reduced to a minimum by standardization, bulk purchase of material, and such preparations as will ensure continuation of construction—has been accepted without real question, although it has emerged that financial considerations, especially in small, struggling undertakings, militate against development in this way.

As regards Conclusion (12), we admit the force of the criticism that we have been too sweeping in stating that electrification should proceed in all areas over which powers of supply are held. Obviously the statement should be read in conjunction with the finding arrived at that it does not appear economically possible at present to attempt electrification in areas where the density is less than 75 persons per square mile. Moreover, just as in the case of densities of 100 and 150 persons per square mile, the rural areas should for purposes of more effective control and development be associated with an established urban undertaker, as clearly adumbrated in Figs. 5 and 11.

Conclusion (13)—as to goodwill and co-operation between all concerned in development even in areas of population having densities little above 75 per square mile—was challenged on the grounds that it was probable that such a meagre population would not be sufficiently wealthy to give the estimated revenue of £10·06 per consumer. We would ask these critics to await further results which, we are confident, will justify our figures, especially if allowance be made for the extended use of electricity for water and space heating and cooking which experience shows does follow upon a wisely devised tariff (see Table 10). The wording "goodwill and co-operation" was introduced designedly, and more particularly because we know how difficult it appears to be for companies and local authorities to work together for their mutual benefit.

Having now referred to the salient points that emerged from the discussions, we propose to proceed to reply to certain matters in greater detail. We find that it is convenient to summarize our replies under separate headings.

Units sold per £ of Distribution Capital Expenditure.

Notwithstanding the advance in the distribution of electricity, the number of units sold per £ of distribution capital invested is not increasing (see Table 3), and we considered this to be a serious matter, but some exception was taken to this view. Mr. Phillips argued that it might indicate that wise and greater provision than usual was being made in anticipation of future demand. Taking the figures for 1928–29 (Table 3), it will be seen that 50 units at 0·97d., being a total of 1·38d. per unit sold (as shown in Table 2) minus 0·41d.—i.e. the cost of electricity sent out of the generating stations and of bulk supplies—is about 4s., or a return of 20 per cent on the distribution capital invested. If we attempt to reduce the sale price to 0·75d. less, say, 0·35d. per unit for generation and bulk transmission as a desirable objective, the return on the distribution capital would be only 1s. 8d. in the £, or just over 8 per cent, which is clearly insufficient. It follows that the number of units sold per £ of capital must be made to increase and the price per unit sold to the consumer to fall, but for the past 7 years this is shown not to have happened. We still hold, therefore, that this is a serious matter, and Mr. Kennedy's and Mr. Phillips's remarks have made it abundantly clear.

Size of Model Scheme Area.

Our conclusion was that an area of not less than 400 square miles in extent should be considered for electrification, and multiples of unit up to 3 or 4 times might conceivably give better results. Mr. Phillips thinks that an area of 400 square miles is too large to be administered from one organization, while Mr. Siviour agrees with our choice of a hypothetical area. Although Mr. Britton sees no justification for stating that the size of an area should be 400 square miles or any other figure, he agrees that they should, for reasons of economy, be as large as possible. He thinks that rural electrification should be linked with a fully operated established undertaking in an urban area, because when so attached more rapid expenditure of capital is possible, owing to the financial support obtainable during (presumably) the earlier stages of rural development. Mr. Margary's attitude generally confirms Mr. Britton's views. In these remarks we seem to detect a clash of interests, or rather a difference in point of view as between local authorities and companies engaged in tackling the problem of rural electrification. When deciding upon a suitable size of area we had only in mind a practical and economical solution and, as a matter of fact, we have contemplated centring our scheme on an established urban centre, as we thought would be evident from a careful inspection of Fig. 5, in which the centre of the Model Scheme area is a town provided with a grid supply. We cannot make it too clear that we have considered our Scheme as being controlled from an urban centre where electricity is available and where a company or local authority is charged with the business of distribution. In these circumstances we contend—and there has been no sufficient evidence to

refute our contention—that the surrounding rural area can be electrified to an extent much greater than has so far been deemed possible without adding to the town dwellers' responsibilities, except temporarily in the shape of credit facilities to finance the project. When that period has elapsed, we have shown that a scheme of expansion will prove to be an asset. In the case of a company this responsibility would be borne by the shareholders. We have contemplated sharing in the distribution and management expenses in a way one might assume to occur in practice, and we shall refer to this a little later in our reply. Where the rural areas surrounding a town are in the hands of companies we see no reason to modify our general assumption as to control and management from some convenient point at the costs shown.

Mr. Britton suggests spheres of operation centred on existing urban points of supply well chosen so as to cover the whole of our occupied areas more or less uniformly, having regard to minimum distribution costs. To this we would agree as being an ideal arrangement, provided some commonsense agreement could be come to between local authorities and companies, both of whom are engaged in this important public service. It may happen in these circumstances, as it does now, that the best placed local authority undertaking operating, say, a small urban supply is neither wealthy nor feels itself in a position to launch out into rural electrification. In such circumstances confidence is absent and the spirit of adventure is damped. Some financial backing is required in the form of a guarantee from a central fund or from the reserves of amalgamated interests dependent on development work for their existence and steady progress.

Density of Population.

Population per square mile has been said to be not quite the most convenient basis for the purposes of computing estimates for a rural area. Mr. Fennell and Mr. Britton both suggest "consumers per mile of line." This unit is quite satisfactory when considering l.t. distribution as shown in Fig. 13(*a*), but it is unwise to include the length of h.t. line in this figure as it bears no relation to the number of consumers. We have gone to some length to explain the dispersion of the rural population in relation to the electrical load, and it must be understood that when a population density is referred to we must imagine an area normally split up into parishes, each parish consisting of 4 square miles. A parish is assumed to contain one village in which roughly 80 per cent of the people in the parish are living, and the varying sizes of the villages are in the proportions set out in Table 22.

Lay-Out (*Fig.* 11).

Fig. 11, in which are shown 33 000-volt radial feeders, is purely diagrammatic and is drawn simply to indicate that a supply of electricity at 33 000 volts is available at the centre of each 100-square-mile area. In actual practice these feeders will either be duplicated or in the form of a ring main.

In answer to Mr. Biles and others, the voltage at these four points has been assumed to be controlled. It would not, of course, be possible to have a voltage variation of 12 per cent at these points and to keep within the statutory requirements at consumers' premises.

Tariffs.

At least fifteen members have referred to the question of tariffs applicable to domestic use—some at considerable length. We pointed out in the paper to the need, if schemes were to be successful, for a suitable tariff, and by a suitable tariff we meant (*a*) a simple one, (*b*) one having some relation to the demand made on the capital and service of the undertaking, (*c*) one inducing the consumer to use more electricity, and (*d*) one that studies the consumer in respect to payment, etc. From the examinations made and recorded in Figs. 9 and 10 we came to the conclusion that a tariff for domestic purposes under which the charge for electricity is reduced in some relation to consumption would perhaps, in all the circumstances, be the best to adopt. That there is need for revision cannot be doubted. Mr. Macleod says that in his opinion there is a great need for the simplification of tariffs and that when a reasonable and readily understood tariff is available custom automatically and rapidly develops. Mr. Siviour is definite about the need for a suitable and attractive tariff; Mr. Nimmo's chief criticism is that the paper lacks a model tariff; Mr. Hetherington refers to the prevailing wide diversity of tariffs and the necessity for uniformity so as to avoid clash and confusion at the borders of contiguous or neighbouring areas, and thinks that at any rate the form at least of the tariffs should be the same throughout; while Mr. Mounsdon hopes for our further remarks.

It may be as well to explain at once that the form of the curves shown in Figs. 9 and 10, on which our estimates of units sold and price per unit for the Model Scheme revenue are based, show the position for 1929–30 only. In the course of time the curves in Figs. 9 and 10 should drop little by little to correspond to the average revenues per unit sold (given in Table 2), but whether the curves will tend to tilt downwards at point B with the point A more or less fixed is a debatable point. It should do so, we think, with improving load factor and increased units used per £ of capital (Table 3).

We felt safe in using the figures we did when they were those of a year that had passed. Mr. Woodward thinks it dangerous to have mixed up power units and domestic units. A separate curve covering sale price and consumption for electricity sold for "domestic purposes only" was derived from the same 221 returns and was found to coincide closely with the left-hand portion of the curve. The industrial unit readings were found to follow the flatter part of the curve shown on the right-hand side with the average revenue of 0·72d. per unit sold (see prices assumed for Model Scheme, Table 16B).

Referring to the formula (1 140d./units sold) + 0·73d. for the Fig. 9 curve, further investigation tends to show that the figure of 0·73d. is higher than, and bears no close correspondence to, the actual running cost of the unit to the consumer. With bulk supply at £3·25 + 0·2d., the average running cost is calculated to be about 0·4d. Mr. Porter's remarks in this connection are interesting and instructive. It seems clear that the unit charge as now made usually carries with it about 45 to 50 per cent of

fixed charges. This, we think, is generally realized and is confirmed by Mr. Long's remarks.

This mixture of fixed and running costs as usually reflected in the running component of our 2-part tariffs does not by any means do what supply engineers want, i.e. increase the number of units sold per consumer or per £ of capital expended. It indicates rather that we are still in a transitional stage as regards tariffs, and are moving slowly from a flat-rate unit charge, which was more suitable for the days when electricity was sold for lighting only, towards a 2-part tariff suitable for all domestic purposes, including small domestic power, and cooking, water- and space-heating, in which, after fixed charges are satisfied, every additional unit is sold at a figure closely approximating to the actual "running" cost of producing and distributing it. If we admit a transitional stage then it follows the right course to take,

TABLE A.

An Example of a Domestic Two-part Tariff, the Fixed or Service Charge being computed on a Proportion of the Units Metered being sold at 8d., and the Unit Component Charge being graded. Minimum Fixed Charge 6d. per week or 26s. per annum.

Annual consumption		Fixed or service charge for range given in cols. 1 and 2	Actual fixed or service charge for range	Unit charge on full quantity metered	Average total bill to consumer for range given in cols. 1 and 2
From	To				
kWh	kWh	per cent	£ per annum	d.	£
0	226	—	—	8·00	—
226	1 000	25·5	5·20	1·25	8·39
1 001	2 000	8·0	4·00	1·00	10·25
2 001	3 000	4·28	3·56	0·85	12·29
3 001	4 000	3·00	3·50	0·75	14·41
4 001	6 000	3·00	5·00	0·60	17·55
6 001	8 000	3·00	7·08	0·50	21·68
8 001	10 000	3·00	8·93	0·45	25·84

For Consumers on 2-part Tariffs:—

For quarterly charge multiply quarterly consumption by 4 and use the corresponding service and unit charge.

For monthly unit charge multiply monthly consumption by 12 and use the corresponding service and unit charge.

whenever the occasion arises to reduce tariffs, is to make the reduction on the unit component of the 2-part tariff. All that we intended in suggesting the form of 2-part tariff shown in Table 19 was that whatever the basis of the ascending "fixed or service charge" might be—whether room area; kilowatts actually measured or allowed for by means of graded sizes of meters; lamps installed; or finally by unit consumption; it should be smoother in ascent, and so formed that the unit component charge descends so as to be an encouragement to increased consumption. In the light of the discussion, and having in mind the fact that electricity for lighting is a marketable commodity at 8d. or 9d. per unit, cooking at round about 1d., and water- and space-heating at about ½d., we now suggest a slightly modified alternative form of quantity tariff to that shown in Table 19, based as before on unit consumption (see Table A). It is true that graded tariffs with the fixed charge based on other than unit consumption are now in force—*vide* Northampton where the fixed charge is based on net rateable value duly graded, and a unit charge also graded in two steps at ⅞d. and ½d.; Bedford, with a somewhat similar scheme but more roughly graded as to service charge with seasonal variation in the unit charge fixed at ½d. for the urban zone, and North Ireland, with a fixed charge based on aggregate floor area (external measurements) duly graded on a unit of area basis, with a stepped unit charge of ¾d. and ½d.

Notwithstanding Mr. Fennell's remarks, this domestic tariff is feasible and the service charge is based on something tangible in the shape of a percentage of units sold. It is easily understood and could be clearly indicated on the back of the meter card and as clearly explained. With the exception perhaps of graded meter sizes it is better, to our mind, than other domestic tariffs in respect to the service charge, because it pays some regard to the load factor that might reasonably be expected with increased output, and consequently to the consumers' kilowatt demand on the system, allowing for diversity. Both components could be slightly increased as the radius of supply was extended if tariff "zoning" were adopted by the supply authority. We think that a tariff of this kind should apply generally at the consumer's terminals whether he is isolated or not. Any further charge in cases of long service or spur lines should be, if regarded as essential (which we do not), a definite amount per annum calculated on capital expenditure as recommended by Mr. Long (see the remarks on spur lines later in reply).

Choice of H.T. Voltage.

Mr. Phelps suggests the use of 22 000 volts for the h.t. network shown as working at 11 000 volts in the paper. His chief reason for advancing this view is that this voltage eliminates the use of much of the more expensive 33 000-volt mains, and the cost of 22 000-volt lines is little in excess of that of 11 000-volt lines. The general consensus of opinion in the discussion is that in this country 11 000 volts is by far the best pressure for local transmission in rural areas, with a 33 000-volt transmission system for bulk suppliers. Throughout the paper we endeavoured to keep to generally accepted standards endorsed by the Electricity Commissioners, but in the case of the North East Coast, where conditions are such that the proportion of industrial load is greater than that taken for the Model Scheme, and where the size of the area and average conditions differ from those which we assumed, we would not suggest that, considering the year in which it was designed, 22 000 volts may not have been the best pressure to use. We feel, however, that if the system were to be re-designed in the light of present experience and practice, the transmission and distribution arrangements suggested in the paper might greatly influence the mind of the designer.

Spur Lines.

The means suggested in the paper of reducing the cost of 11 000-volt spur lines, namely by using a small copper conductor in conjunction with short spans, has

been severely criticized. This method of construction is almost universal outside this country, and the cheap Continental lines referred to in the discussion are of this type. The whole question hinges on wayleaves. If wayleave troubles are absent then a line built up of a small copper conductor, say No. 6 S.W.G. with spans of 180 ft., strung entirely on pin insulators, will invariably prove cheaper than a steel line with a longer span. On lines feeding an isolated consumer (and this is the kind of line that is under discussion), wayleave troubles are more likely to be absent because the line often runs over the land belonging to the consumer.

The problem of connecting up isolated consumers is a difficult one from both the technical and economic points of view. It can only prove lucrative if the undertaker is in a position to offer a tariff that urges the consumer to make full use of electricity, and every assistance should be given to the isolated consumer, always provided that consumers of other categories do not unduly suffer. From the statistics in the paper the average revenue per farm is approximately £11 per annum. This is lamentably low, and it is obvious that electricity is employed for little else but lighting. The judicious application of electricity to agricultural problems affords immense scope. The load factor of an individual farm at its best will be poor, but diversity among farms should be high. There is therefore every reason for connecting up as many as one can, and the possibilities are that the maximum demand for this class of consumer will occur at a different time from that of the town load. Mr. Phillips has shown that the maximum demand of his rural area may occur in the summer months; this, of course, improves the general load factor—a result highly to be desired.

For isolated consumers Mr. Long indicates a satisfactory way of arriving at an annual charge on special local expenditure incurred, to which must be added the usual consumers' 2-part tariff with a unit charge carrying a high proportion of fixed costs. We agree, provided the course recommended on page 216 of the paper was deemed unsuitable. It is perhaps unfortunate that every isolated consumer should actually be treated differently as regards payment for a supply. Mr. Long's method is no doubt the fairest. The other alternative is to base a tariff on the size of transformer. This appears to be reasonable in most cases and works well in practice, but it does not take into account the length of spur line, i.e. the cost entailed in reaching the consumer, which is usually a matter of a separate charge and checks business.

Mr. Perks raises an interesting point in this connection. It is not at all safe to assume, he says, that any proposition is a paying one if the revenue is fixed at 20 per cent of the capital cost. Whether it pays or not, he continues, will depend on the average price at which the unit is sold. A low-priced unit, he points out, inducing large sales, gives no greater total revenue than may be expected from the sale of a few units at a high price, calls for greater capital expenditure, and may only be satisfied by a higher return than 20 per cent on the capital expended. He therefore stresses the advisability of some revision of the Clauses Act. The argument put forward involves questions of policy as to how developments should proceed, and in the circumstances we can only direct attention to our considered view as expressed on page 216.

Mr. Coe and Mr. Lisle ask what is the best method of dealing with isolated supplies to farms, hamlets, and country residences in patches of sparsely populated areas (say about 65 per square mile). We would refer these speakers to the final paragraph of Section (*f*) on page 217 and say that we would consider this a special circumstance and would probably advocate single-phase galvanized-steel conductor interconnection at 11 000 volts. For dealing with the densities and loadings taken for the Model Scheme we would adhere to our conclusions given in the paper and use 3-phase lines.

Earthing.

The question of earthing has been raised by several members. There is perhaps some confusion in the minds of certain engineers as to what constitutes "earthing." "Earthing" should, we think, be distinguished by reference either to (*a*) the earthing of the l.t. neutral, or to (*b*) apparatus earthing. With regard to the former, the Commissioners' Regulations require that an earth be made at one point only and that the insulation of the neutral be preserved throughout. The regulation was made to avoid any interference with the operation of telegraph and telephone circuits. In these conditions, i.e. earthing at one point only, there may obviously be a considerable voltage-drop along the length of the neutral in the event of a short-circuit occurring at the end of the l.t. line remote from the earth. Consequently it is possible under certain circumstances for the voltage to rise sufficiently to make the line dangerous to touch. The answer to Mr. Kennedy is, therefore, that so long as multiple earthing is prohibited we cannot advise the use of an uninsulated neutral conductor under eaves or elsewhere. We fully realize the danger of a badly insulated neutral earthed only at one place.

In our opinion it is imperative that all low-tension apparatus should be well and securely earthed, either to the water supply system or some tested earth on the premises. Where, in unusual circumstances, this is found to be impossible, we recommend a local continuous earth wire, earthed wherever most convenient.

As to high-tension line earthing, we can only reiterate the opinion that we expressed in the paper. As to the remarks made on this subject by Mr. Babb, Mr. Fennell, and Mr. H. W. Taylor, we realize that in exposed hilly country a continuous earth wire placed above the h.t. conductors will tend to eliminate lightning troubles, and in such circumstances we would advocate its use. Mr. Biles raises the question of the best type of earth electrode to employ. This is still a moot point but from recent investigations it appears that an iron rod about 8 ft. long by $\frac{3}{4}$ in. diameter gives as good a result as any of the other types. The use of crushed coke has been discredited because it has been found that as good an earth can be made without it as with it. It may be interesting to note that where lattice steel towers are used with earth grillage foundations, the foundations offer a lower resistance to earth than the usual earth electrode.

Acts and Orders.

Mr. Siviour questions our assertion that the Acts and Orders are no impediment to development, and says that they require clarifying, and Mr. Woodward is of the opinion that the option to purchase by a local authority forms a definite bar to progress. This may be so in cases where the option to purchase is near at hand, and no doubt some of the Acts and Orders would be better for revision, so putting the authorized undertakers on a sure footing and inducing expansion. We are heartily in agreement with Mr. Siviour when he suggests that a codifying Act would be a useful addition to our book-shelves.

Commissioners' Regulations.

In the paper we stated that the Commissioners' Regulations do not offer any obstacle to the cheap erection and design of overhead lines, and we see no reason, as the outcome of the discussion, to modify those views.

As Mr. Nimmo points out, many h.t. lines are erected in excess of the requirements of the Regulations, thus unnecessarily increasing cost. With regard to general criticism on the score of cost, it may be pointed out that in the case of l.t. lines it is usually found essential in practice to erect larger-diameter poles than the Regulations actually demand, in order to enable service lines to be taken off neatly.

As to h.t. lines, Mr. Fennell, Mr. H. W. Taylor, and Mr. Hill emphasize the necessity of the continuous earth wire, but in our opinion, as given in the paper, it is not always necessary, and saving can frequently be effected by omitting it.

It is not within our province to express any definite views as to whether any relaxation of the Regulations in respect of factors of safety, etc., is necessary or desirable. Whatever variations may be made from time to time we do feel that, as a practical point, reliability should under no circumstances be sacrificed by those engaged in supplying rural areas.

L.T. Distribution Networks.

Village Distribution Networks.—Mr. Fennell suggests that the lay-out of pole transformers, substation, and low-tension 3-phase 4-wire 400/230-volt network, as fully described in the paper, is or will be generally unsuitable and uneconomical, because he says that the whole tendency is towards ribbon growth in rural areas. Although we think he is mistaken in assuming that no check will be placed on ribbon growth, an h.t. and l.t. system with suitably spaced transformers is most suitable and flexible for this kind of housing development. There is no doubt that in some spoilt areas this system of distribution is the best, and here we would endorse Mr. Fennell's suggestion, but it cannot be said to be of general application. It is usually found that a long, straggling village can be well catered for by two substations, the chief point governing a lay-out being the voltage-drop. The position of the substation is more often than not governed by geographical and wayleave considerations.

We admit that the use of No. 8 S.W.G. copper conductors for l.t. mains can only be justified in the smallest of hamlets; the poles should be such that a larger size of conductor may be strung on them at a later date. The saving in using No. 8 S.W.G. is very small and we further admit the argument that it might be well in practice to have 0·05 sq. in. as a minimum size, as so little will be added thereby to the cost of equipment.

It is impossible to say that no l.t. lines should exceed a certain length; such a ruling may be possible in an urban area where consumers are more or less evenly spaced, but for rural work it appears to us to be out of the question. It must not be assumed that the length of l.t. main shown in Table 24 represents long, straight runs. The length may be made up in shorter star-shaped amounts.

As to the point raised by several speakers, including Mr. Fennell and Mr. Turnbull, whether a very definite saving might not be effected by the use of single-phase 3-wire distribution in the smaller villages, we are in agreement, where there is an absence or no likelihood of power load. It has several real and obvious advantages, including cheapness, but it should be adopted with great caution as one can never foresee what industrial development may arise in a rural area. We do not advocate its almost general use as does Mr. Turnbull, but for small hamlets at the end of spur lines it is perfectly satisfactory. It was not included in the paper, because it would have been difficult to assume exactly where single-phase and 3-phase supply should be used, but a scheme such as the Model Scheme with some single-phase networks would have been cheaper. We felt we were right and safe in budgeting for a 3-phase system.

Voltage Regulators.—Mr. Norris and Mr. Ayres raise the question of automatic voltage regulators. The chief difficulty in a rural network when it becomes fully loaded or the load in a portion develops more than is estimated, as is often the case, is regulation, and it is in such circumstances that an automatic voltage regulator appears to us to be a sound proposition. In this connection the question of voltage variation at consumers' terminals must also be considered. The maximum variation permitted by the Regulations is $\pm$ 4 per cent of the declared voltage. Mr. Britton suggests that a greater variation should be allowed. We do not hold this view, because if a cooking load is anticipated, as it must be, nothing can be more harmful to the reputation or the usefulness of electricity than a severe voltage-drop at the cooker.

There are two aspects of the question as to what saving can be effected by the use of voltage regulators. The first is whether greater saving could not be made by installing them to cope with excessive voltage-drop as and when unexpected demands occur in the later stages of development. In this case it is purely a question of balancing the advantages of (*a*) the cost of erecting new or larger mains, (*b*) an extra feeder, (*c*) a new substation, and (*d*) a regulator. It is fairly certain that unless the increase in load is excessive the regulator will give the greatest saving. The other aspect is as to whether it would not be better to install a regulator at the commencement, so compensating for all the h.t. voltage-drop. From this point of view the engineer would, from the start, be able to work out his network for a higher density than would be possible without one. Fig. 29 illustrates this point. Owing to the reactive

drop a conductor larger than 0·1 sq. in. is not economical, so that there is a definite limit to conductor size on this basis. Should the estimated load call for higher current densities, an automatic regulator may be considered at the start. The extent to which one should go with a regulator should be influenced by Kelvin's law.

H.T. Lines.—Mr. Siviour and Mr. A. B. Mallinson question the economic span suggested in the paper for the 11 000-volt single-conductor line. On page 212 of the paper we have stated very fully our reasons for adopting 350 ft., but we quite agree with these speakers under the conditions they assume. We can only repeat that so much depends on local conditions and we adhere to our general conclusion.

Two speakers are of the opinion that the extra precautionary measures at road crossings required by the Regulations are unnecessary, and that the abolition of road-crossing construction would be an effective means of cheapening overhead lines. The need for increased safety at public roads is generally recognized throughout the world, and some measures are required by practically all countries on the Continent. The prevailing practice is to increase the factor of safety of the support at the roadside. The Commissioners' Regulations are lenient on this point.

Pole-Top Fittings.—The pole-top fittings illustrated are representative types, and many variations of and improvements on these types exist. The one which we suggest, shown in Fig. 18, has some marked advantages over others enumerated in the paper. A tipped triangular spacing, as represented by Fig. 21, is the best. This type of spacing, as Mr. Phillips points out, has a slight advantage which none of the others possesses, viz. the pole is concentrically loaded. This, however, is not of any real importance, because the vertical weight is so little as to be negligible compared with the transverse wind load which acts at right angles to the pole. The most efficient type of pole top is a variation of Fig. 22, giving a tipped triangular spacing; but this type of construction is more difficult to erect and is of less general utility than that of Fig. 18.

Mr. H. W. Taylor is of the opinion that at medium-angle positions it is cheaper to fit a strap at right angles to the cross-arm and put the insulators in that. We agree and would say that this is quite satisfactory, provided the strap and single cross-arm are sufficiently strong.

Foundations.—With regard to pole foundations, we suggest that on such sizes of h.t. lines as are recommended in the paper it is necessary to fit kicking blocks on all intermediate poles, except in the case of rock foundations, so as to be assured of a firm hold. The design of pole foundations requires judgment, and much must be left to the engineer who is erecting the line. It can, however, be generally accepted that kicking blocks are essential for lines having spans of over 300 ft. Where they are used the advantage of using a machine auger for digging the holes is, of course, negatived. It has been suggested that the pole should be planted 1 ft. deeper instead of using kicking blocks, but this depends entirely on the ground in which the poles are to be planted. We would not suggest that this could be accepted generally.

Low-tension Construction.—Low-tension overhead line construction is rapidly becoming standardized in general practice, and the construction shown in Fig. 32 is being adopted almost universally. Mr. Turnbull says that the Aylesbury type is superior, but this type can only be used at straight-line and small-angle positions. At section, large-angle, terminal and junction-poles, one is forced to resort to "D" irons, and as straight runs are rarely met with in low-tension work we fail to see the advantage of this type of construction. It also has not the facility for taking off services that a "D" iron has.

Mr. H. W. Taylor's Fig. H is undoubtedly an improved variation on the "D" iron construction, and his suggestion clearly illustrates the facility with which services may be taken off.

Several speakers, including Mr. Kennedy, question the advisability of placing l.t. lines at the backs of houses. We made this suggestion with certain reservations. Mr. Britton has, however, erected a complete l.t. network in a village in which all the lines are at the backs of the houses. It is a most excellent job, the lines being scarcely visible from the road.

Substations.—The substation designs indicated in the paper represent types of construction which are in general use, each type having advantages and disadvantages, and, as usual with designs of this description, being a compromise. From the discussion several very definite points have emerged on which nearly all the speakers were unanimous. The fuse links shown in Fig. 25 have proved to be of little practical use, owing to the difficulty of operation. We fully realized that this type of link is not all that could be desired, but we felt that for such a small load as 5–15 kVA it scarcely warranted the more expensive pull-down type. The main factor influencing our choice was cost. We are of the opinion that if a better type can be used without unduly influencing the economic aspect this should be done. In Fig. 26 the position of the l.t. fuse box has been much criticized. Mr. Phelps, Mr. Lisle, and Mr. A. B. Mallinson have suggested that this box should be in such a position that it can be easily reached by an operator standing on the ground. This is undoubtedly the best position. A cabinet either of timber or iron can be fixed to the pole leg and it can contain fuses, links, and plugs for fitting a meter and perhaps a maximum-demand indicator. This is an undoubted improvement.

A certain amount of controversy has ranged round the question as to whether h.t. air-break switches, oil fuses, or oil circuit-breakers should be used. Obviously the choice largely depends on the position in the system where the apparatus is to be employed. For sectionalizing purposes an air-break switch is all that is required, as well as at those definite points on the system where fairly large loads are tapped off. For tappings for 100 kW or over, a resetting oil circuit-breaker is undoubtedly the best. At less important positions oil fuse-switches may be used successfully and these should be of the type in which, if one phase breaks down, all three phases are tripped out. Furthermore, with overload oil circuit-breakers at selected points on the system a certain amount of protective discrimination may be arranged.

We were interested to learn from Mr. Coates that the cost of these switches is comparable with that of oil switch-fuses. We realized that the main disadvantage of fuses is that they require more or less skilled persons to replace them. On the other hand it must be remembered that they do not blow out unless something radically wrong has happened, such as would necessitate the presence of a skilled man.

There is a certain amount of disagreement as to whether the h.t. side of transformers should be fused. Mr. H. W. Taylor, Mr. Turnbull, Mr. Burton, and Mr. Siviour are definitely of the opinion that h.t. fuses to protect transformers are essential, while Mr. Phelps and Mr. Lisle deprecate their use. It is difficult to reconcile these conflicting opinions, but it appears to us that h.t. fuses are essential in nearly all cases for rural work.

Mr. Lisle makes the interesting suggestion concerning the standardization of transformers that the idea of a transformer of a smaller size than 25 kVA should not be entertained, and that when the load grows another 25-kVA transformer should be added and worked in parallel. It would undoubtedly prove useful in certain areas to have one size of transformer, but it is doubtful whether the idea could be applied generally.

We stated that transformers of over 50 kVA should be placed on the ground. Mr. Latham has placed 125-kVA transformers on a pole platform: here again this type of construction may prove successful in particular circumstances, but generally we do not think it would prove satisfactory.

Dr. and Mr. Ekstrom's Communication.

The mathematical analysis of the problem of electrical transmission in sparsely populated areas is useful and instructive. The main difficulty, however, in approaching this problem is the uncertainty of practically all the constants. Consequently, after making a complete survey of an area and estimating, as accurately as one can, the likely electrical load and then designing the schemes on the lines laid down by Dr. Ekstrom, the very first thing that would happen would be an enormous load development where it was least expected, and the economies he anticipates from the tapering of the conductor size would be seriously miscalculated. The main difficulty that we foresee in starting off with a large-diameter conductor and tapering down as the line goes to the outskirts, is the variety of size of pole and the variety of span length that will be needed. This, of course, would increase erection costs enormously. One point to remember is that in the United Kingdom great care is always taken to utilize the most economic spans for the conductor on wooden pole construction, whereas in most other countries where timber is cheap this is not so evident. Abroad, use is made of two or perhaps three standard sizes of poles. They do not depart from these standards, nor as a rule from the length of span; and on these poles they string whatever conductor they wish—in some cases irrespective of what the pole will really stand. Dr. Ekstrom's scheme would be quite satisfactory for a uniform span, where a uniform pole could be used and where the only variation would be the size of conductor, but we do not think a lay-out on his lines would be cheaper than the usual practice now followed in this country.

Capital Costs.

The tables on page 226, in which the capital expenditure is set out, give costs of overhead lines and equipment on the basis of copper at £55 per ton. For this paper to be of use one must vary costs to suit local conditions. The costs of h.t. lines in the paper must not be compared with the costs of short lengths of line erected over particularly bad country in particularly bad weather. Mr. Matthews and Mr. Coates have given particulars of some very cheap lines. Such costs are apt to be very misleading. Price must be qualified by the line pressure, conductor size, type of support, and the Regulations to which the line is designed and erected. Again, the cost of erecting lines in a highly developed country like the United Kingdom is quite a different matter from that associated with the erection of lines in a new and undeveloped country. From the discussion it can be concluded that the majority of speakers regard the costs in the schedule as reasonable.

Our figure of £2 per overhead service is perhaps the most often criticized item. It includes only a loop-in from the l.t. pole to the consumer's premises, and this estimate includes insulators, bracket, one insulated service wire, and one bare neutral, leading-in tube, meter board, and fuse. It is assumed that a number of consumers in terraced houses may be connected from one service. What might be termed a long service line is not included in this figure as it is amply covered in the l.t. distribution costs.

We have found that the estimates for substation equipment, etc., are on our further revision quite reasonable. The large increase in cost of a 75-kVA installation over a 50-kVA installation is entirely due to the fact that at the former size we have allowed for three sets of switches as shown in Fig. 27, and that the low-tension arrangements permit of more than one circuit being taken off. As it is essential to have sectionalizing switches at suitable intervals in the network, these have been arranged for at points where loads of 75 kVA and above are estimated to be available. This can only be regarded as a method of allocation adopted as a precautionary means of including all necessary apparatus for the Model Scheme.

Mr. Hill points out that no allowance has been made for Post Office and railway crossings, but it should be noted that a sum of £11 730 has been allowed for 8 miles of h.t. cable. This will only be used in short lengths, chiefly at the entrance to large villages and awkward railway and Post Office crossings.

Revenue Account Expenses.

A considerable amount of criticism has been levelled at the "expenses" side of the revenue account shown on page 227. As to the cost of electricity purchased, we have indicated that the cost, taken at £3 5s. per kW at power factors between 0·8 and 0·9 and at 0·20d. per unit, was simply an estimate based upon what should shortly be the cost of production at our large power stations where, with 90 per cent of plant in use, costs at £2 5s. per kW and 0·110d. per unit should not be un-

common, with a small margin added for the Board's main transmission and other expenses. The cost of bulk supply will naturally, for some time, vary in different parts of the country, but we hope and expect that we have struck a quite possible and happy mean. We are inclined to think so notwithstanding Mr. Purse's references to contracts at £4 7s. 6d. + 0·22d. and £6 5s. + 0·22d. Maybe these tariffs are of quite a temporary nature and due for further investigation, or perhaps they apply where conditions are somewhat extraordinary. We are the more disposed to think that one or the other or both suppositions are true because Mr. Scott observes that he is amused at the criticism of the bulk supply charges as he has actually had a quotation almost identical with the figures quoted in the paper. Mr. Clegg observes that although he can agree with £3·25 he is afraid the figure of 0·2d. is a little lower than most engineers can anticipate. If the supply industry is to prosper, we must be eager to obtain supplies at the absolute minimum because sales prices, and therefore development, depend upon this vital and (for years) immutable factor.

As to the expenses of distribution and management, it has already been explained that in setting out our Model Scheme we contemplated centring our scheme either on an established area of distribution, under either a company or a local authority, or alternatively as part of a larger organization such as may now be found in control over large areas embracing villages, small country towns, etc. Mr. H. S. Ellis acknowledges this assumption but goes on to ask whether we had assumed that the rural scheme would be subsidized by the urban area. The word "subsidized" is, we suggest, wrongly used in this connection. Sufficient has been said in the paper and in our reply as to the revenue side of this account to show that it is a matter of meeting the first 2 or 3 years' deficits by means of a sum on credit duly honoured, as the scheme proceeds, by interest and the return of the loan—an everyday transaction. Mr. Ellis doubts whether the figures taken for distribution expenses and management are sufficient. Mr. Clegg says that the distribution costs are lower than those prevailing in town supplies. Mr. Purse gives a set of figures derived from the Commissioners' Electricity Returns for 1930–1931, extracted by him to prove that we are completely wide of the mark in our estimates of distribution and management expenses. Unfortunately, however, for the careful presentation of fact for which he is entitled to credit, he has omitted to allocate management expenses between generation and distribution, and appears to have had no regard to the intensity of development as indicated by the most important factor derived from the number of units sold per £ of capital expenditure. This is regrettable and we hope that Table B will help to eliminate the false impression he has unthinkingly given. The conditions under which the Model Scheme operates must also not be forgotten.

TABLE B.

Cost of "Distribution Expenses" and "Management" (*being Items* 2 *and* 3 *on Page* 227) *for the Year* 1929–1930.

(Cost of Electricity, Interest and Depreciation Charges, Rents, Rates and Taxes omitted.)

Name	Capital expenditure on distribution	Units sold for local distribution	Revenue	Revenue per unit sold	Distribution expenses	Management (distribution only)	Total distribution costs	Units sold per £ of distribution capital	Distribution costs per unit sold
	£	kWh	£	d.	£	£	£	kW/£	d.
Eastbourne	440 069	15 124	109 365	1·73	4 843	10 744	15 587	34	0·247
Heston	378 772	16 201	102 984	1·52	10 951	4 936	15 887	43	0·235
West Hartlepool	236 371	16 534	81 248	1·18	11 375	3 966	15 341	70	0·223
Grimsby	302 050	16 443	93 029	1·36	8 501	7 558	16 059	54	0·234
Swindon	236 665	15 728	94 778	1·45	6 065	4 170	10 235	66	0·156
Gravesend	201 591	16 342	74 882	1·10	2 429	3 007	5 436	81	0·0798
Model Scheme, 3rd year ..	264 440	6 204	52 470	2·03	3 060	4 410	7 770	23	0·300
Model Scheme, 6th year ..	300 500	16 678	95 900	1·38	3 730	4 735	8 465	55	0·122

It will be seen from Table B that in the Model Scheme the expenses per unit taken for the two main items under consideration are ample, and although the figure for the sixth year is somewhat short of the average of the particular undertakings chosen by Mr. Purse, as a result of our investigations we are confident that if every regard is paid to economy of operation as adumbrated on page 192, and with the same intensity of development, results of the order given in the paper will be achieved.

Under the heading "Rents, rates, and taxes," Mr. Perks does not think that the 1½ per cent capital expenditure on which we have based our estimates is adequate. He refers to the item of 1s. 3d. per pole per annum as insufficient and cites the Ministry of Transport compensation figures of 4s. in arable land to 1s. in hedges, but not all pole rentals are determined by the Ministry of Transport and cost this amount. Some cost nothing but the asking, and with care in overhead line lay-out we are still convinced that, apart from the general expenses of obtaining leave to the route tree-lopping

and fence repairs which we have included in our Statement of Capital Expenditure, the annual rentals should not and will not, under careful supervision and the employment of good wayleave officers with local knowledge, be greater than the amount included, of 1s. 3d. per pole on the average. We have seen records of initial costs of £6 per mile and annual pole rentals of very little over 1s. per pole over wide areas.

Mr. Barrett thinks that assessments, presumably in rural areas, will reach nearly 15 per cent of gross receipts, and the rates 13s. 4d. in the £ (of the assessment). Actual costs of operation do not confirm this pessimistic view. A reference to the Ministry of Health's returns shows that a rate of 10s. in the £ is nearer the average rate than 13s. 4d. in rural areas, and on the basis of 7½ per cent on gross income for assessment purposes—which we consider nearer the mark and worth fighting for—the figure for rents, rates, and taxes given as £4 440 (6th year) is fairly sound. It may be slightly on the low side, but not much. Assessments are not, it must be remembered, based solely on gross income, the item of initial cost being also an important factor.

Turning to the question of capital charges, we wish to thank Mr. Bolton for drawing attention to our figure of 3 per cent for depreciation if taken on a 20-year fund bearing interest at 3·5 per cent. The period of repayment would be about 22½ years, and not 20, as given. We can say, however, that 3 per cent is generally accepted as safe for the class of equipment under consideration.

Mr. Bentham and Mr. Siviour ask where in our accounts we have provided the capital and shown the expenses and income connected with the necessary and most important matter of assisted and rental wiring of dwellings and the provision of apparatus. We have not done so as we felt it would greatly complicate the accounts presented, and we were aware that a separate account must be kept under these headings and should and can be made to balance. We admit that we should have referred to this subject. In this connection we would say in answer to Mr. H. S. Ellis that part of the salary of the sales engineer in the 6th year would rightly be debited to this account, and the sum of £520 in the final year for "Publicity" would be a fair apportionment.

Demand and Revenue.

The criticism directed against the revenue to be expected, as shown on the revenue side of the account, may be placed under the headings of:—

(*a*) The rate at which connections have been assumed to be made over the period of 6 years (see Fig. 4).

(*b*) The rate of increase in revenue per consumer taken (see Table 16B).

(*c*) The number of units sold per consumer, and the revenue per unit assumed (see Fig. 9).

In no part of the paper do we feel more sure of our ground than on this point, as it is based on fact and on the experience of those engaged on the actual work of development. To this statement must be added the further remark that very few, if any, undertakings as yet contain at one and the same time all the ingredients for successful results that are referred to as being the *sine qua non* for the Model Scheme, and further referred to on page 192. The reasoning in the paper is, we think, quite logical. Starting with Fig. 4, the rate of connections there shown is the outcome of the considered opinion of engineers with long practical experience in rural work, coupled with some judgment on our part as to the effect of offering assisted or hired wiring and admitting all the essentials referred to. Turning to the revenue to be expected, the number of units sold and the price per unit were based on the 221 returns analysed in Table 7 and Fig. 9. It will be found that the revenues per consumer adopted for the Model Scheme in Table 16B are based on the formula 1 140d./(Units sold) + 0·73d., on which the curve in Fig. 9 is constructed.

Certain members refer to Tables 11 and 12 and ask whether these figures represent returns which may be expected in rural districts. The answer is "No, not on the average." We produced them for the purpose of indicating what large sales may be effected when electricity can be offered at the prices shown.

On the one hand Mr. Bentham thinks we have greatly over-rated the revenue to be expected under the conditions laid down. Mr. Elliott endorses this view by saying that we are too optimistic as regards domestic consumption.

On the other hand Mr. Long says that his experience is that after 3 or 4 years he is getting sufficient income to cover outlay and all expenses from widespread rural areas surrounding Norwich. Mr. Scott gives instances of highly successful development, one with an average revenue of £7 9s. per consumer at a price of 2·445d. per unit sold, the load factor being 25 per cent with 63 per cent of premises connected, and the results being obtained in the 6th year. Mr. Joseph thinks we have based our demand on loads which are much too light, while Mr. H. S. Ellis thinks our revenues, which he recognizes are based on actual results, do not appear to be very different from what he has been accustomed to. It may, therefore, from this brief survey be said that in our estimates of revenue the honours lie with us. In any event, whether the units sold per consumer are slightly greater in quantity and lower in price or are lower in quantity and higher in price, the revenues will remain substantially as given in the Model Scheme. An ounce of fact is worth a ton of estimating, and although we are unable to give full figures, it is hoped that particulars of the actual results obtained to date in the areas of the two Demonstration Schemes will be included in the forthcoming Annual Report of the Electricity Commissioners. Suffice it to say that, after an average period of availability of supply of 24 months to the villages within the area, about 50 per cent of the inhabited dwellings are now connected.

Mr. Perks raises an interesting point when referring to our conclusion (see page 203) "that any drop in the charge per unit to consumers results in an increase of revenue." He assumes that we are referring to net revenue, i.e. the revenue after satisfying interest and depreciation and other charges on capital cost. He then endeavours to show by means of curves that our conclusion is wrong, arguing that increase of load tends to give a worse financial result. In the first place our statement refers to gross revenue and is conclusively supported by Mr. Phillips, where he gives an instance—one among

many—that a reduction in tariff is accompanied not only by an increase in revenue but also nearly always by larger gross profits. When making our statement we had in mind a well-equipped transmission and distribution system of capacity well in advance of existing requirements, and already subject to full interest and depreciation charges. We are fully aware that further connections mean increased capital expenditure, but we fail to understand Mr. Perks's attitude to increase of load. We may not have fully understood him, but he evidently finds it better to refuse load except for lighting and a few minor uses. Every little increment of load placed on his equipment seems to be the last straw that breaks the camel's back. His argument is contrary to all experience of farsighted engineers. Why should any enterprise be expanded if diminishing dividends or return on capital is permanently to be the result?

Sporadic Development.

In several places in the paper we have emphasized the necessity of preparing a complete scheme. Whether it is carried out all at once is not of great moment, but it is essential that the main framework should be prepared from a careful and complete survey. Mr. Phillips says that the Bedford scheme will prove whether one is justified in carrying out the complete scheme as early as possible, irrespective of potential revenue. The opposing view to this is what might be called peaceful penetration, i.e. waiting for each link to pay for itself before proceeding with further work. This, indeed, will be satisfactory, provided the ultimate and complete scheme is always kept in view, but if mains are cut down to suit the immediate load so as to ensure an immediate lucrative return, it will be very doubtful whether these mains will afford a suitable basis on which to expand, and so development will be hindered from the start. As to likely projects, we appreciate and agree to Mr. Perks's suggestion that some factor of wealth of an area would be the greatest value in determining whether or not to attempt development in a hitherto untouched area. We can think of nothing better than to take net rateable value (i.e. the value of property on which rates are levied) per head of population and relate it to some "standard" area and successful scheme. In this connection Mr. Britton submits very useful information when he says that experience teaches him that most country folk are willing to spend on electricity an amount equivalent to half the annual value of the premises they occupy, the exact figure depending upon their wealth and their desire for comfort.

Mr. Bentham and Mr. Phelps refer to the important subject of farm load and our average return of £11 per farm per annum. We are glad to note their optimistic view that in Table 10 this might be taken to yield £50 in place of the £20–£25 there estimated. The actual result given in Table 7 was, for the investigation therein recorded, £11·1 per annum. We can only repeat that we are confident that this actual poor result is due to the custom of loading an isolated consumer with so many initial charges (e.g. for erecting the usually needed spur line and transformer, etc.) that he has no money left to buy electricity and to continue buying it in quantities useful to himself and to our industry. We have referred further to this matter under the heading of "Spur lines."

In answer to Mr. W. T. Taylor, we have, as will be seen in Table 16A, estimated that the units which could be sold in the 6th year in our Model Scheme would be, for domestic and industrial use respectively, 9·5 and 7·2 millions. We consider that the proportion of industrial units taken represents a cautious estimate based on general information contained in the Commissioners' publications. Our omission to include revenue for street lighting is referred to by several speakers. We are glad to learn that electricity is more extensively used in village streets than we had thought. We did not include it as a separate item, chiefly because it would have unduly complicated the Model Scheme. This type of load may prove valuable and should certainly be sought. One of the advantages of overhead line conductors is that the poles may be used for lighting standards. In some of the smaller villages street lighting has been found to increase the rates materially and has therefore been discouraged.

Finally we would reiterate that we feel that the receipts shown on the revenue side of the account for the Model Scheme have not been assailed with success and that they may be accepted with confidence.

Conclusion.

We feel particularly indebted to the very able and concise criticism offered on our paper by members in responsible positions, and intimately engaged in pioneer work in rural areas. Their remarks form a most complete survey of the subject. The careful analysis of the proposals and conclusions at which we arrived has, we think, brought nearer a solution of the problem of rural electrification. The interest evinced, especially on the subject of tariffs, shows how much wider is the issue than that of rural work. We cannot conclude without acknowledging our indebtedness to Dr. Ekstrom and Mr. Ekstrom for their most able electrical analysis of the economies of voltage and conductor selection, and to Capt. Hines for his contribution on the economics of plant provision, the latter a matter not brought into the discussion but of intense interest to us and no doubt to other members engaged in rural development.

DISCUSSION ON "DIELECTRIC PHENOMENA AT HIGH VOLTAGES."*

NORTH MIDLAND CENTRE, AT LEEDS, 8TH DECEMBER, 1931.

Prof. E. L. E. Wheatcroft: I think we shall understand the subject of the breakdown of air better when we know more of the conditions of the ionization which occurs in the air. Although we know little at present about the mechanism of air breakdown, one of the facts which we have regarded as definitely established is illustrated in Fig. 1. This illustration was produced for quite a different purpose from that of explanation, and I have therefore extracted the essential parts of it for that purpose and incorporated them in Fig. E. This shows the characteristics of the breakdown of a sphere-plane gap. The curve OPR gives the breakdown voltage for a sphere of 25 cm radius, and the curve OPQ the voltage at which corona first appears. It is seen that in the range OP the formation of corona is immediately followed by breakdown, whereas in the range PQ–PR corona forms at a lower voltage than that required for breakdown. This has always been explained by assuming that corona tends to enlarge the effective radius of the sphere. If the centre of the sphere be kept fixed, enlarging the radius brings into play two opposite effects. The one is to reduce the length of the gap, and this tends to encourage breakdown; the other is to reduce the concentration of lines at the surface of the sphere, due to the larger effective radius. The region OP of Fig. E is that where the first effect is preponderant and breakdown is encouraged by the formation of corona; in the region PQR the second effect is preponderant and the breakdown voltage is raised by the increase of effective radius. Following Peek's† formula for voltage gradient between two equal spheres, it is possible to calculate the critical spacing for a given radius. The unstable condition is found to occur if the spacing is less than twice the radius of the spheres. On the analogy of this result for two equal spheres, we should expect the critical spacing for sphere and plane to be equal to the radius of the sphere. The critical voltage found by the authors is indicated by the point P (Fig. E) for a 25-cm sphere, and by the point R for a 50-cm sphere. In both cases the critical spacing is 4 times as large as we should expect from Peek's formula. The discrepancy might be due to the fact that the plane was small compared with the infinite plane demanded by theory, but in that case we should have expected a greater discrepancy at larger spacing and larger sphere diameters, whereas the ratio 4 : 1 seems to be fairly constant throughout all the results obtained by the authors. The most interesting part of the paper is the exposition of the theory of thermal breakdown. We have already discussed the difficulties involved in the usual overvoltage test, and we now find it possible on the thermal theory to correlate expected breakdown voltages with the results of inexpensive tests of dielectric losses. It would have been interesting to have had more experimental confirmation of the theory of thermal breakdown. This subject is dealt with in detail by Joffé, and I propose to show as lantern slides three diagrams from his book.‡ The first slide, reproduced from Figs. 48 and 50, gives the circuit to which a crystalline dielectric is equivalent, and the expected variation of dielectric power factors with frequency. According to Joffé, figures for glass and paraffined paper agree well with such a curve. The next slide, reproducing Fig. 53 of the book, shows the variation of breakdown voltage

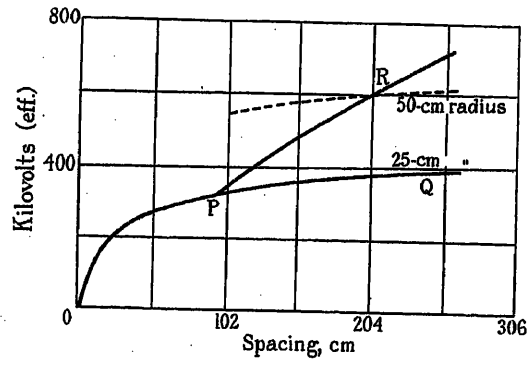


FIG. E.

and resistivity with temperature for two kinds of glass. According to theory, $\log (V)^2$ and $\log \rho$ should both give straight lines when plotted against $1/T$; the slope of the $(\log \rho)$ line should be slightly greater than that of the $\log (V)^2$ line; and the difference $[\log (V)^2 - \log \rho]$ should be the same for two different kinds of glass. All these points are confirmed in the results quoted by Joffé.

Mr. B. D. Youatt: It is interesting to note that Fig. 1 shows a constant ratio of about 3·7 between the critical gap and the radius of the sphere in a sphere-plane gap. The curve for the point-plane gap follows the critical spacings for the sphere-plane gaps, and it is consequently easy to determine the critical gap and voltage for spheres of any size. The radius of the sphere multiplied by 3·7 gives the critical gap, and the breakdown voltage of that gap (obtained from the point-plane curve) gives the critical voltage. The authors raise the question of electric wind and precipitation and couple this with the problem of the contamination of insulator surfaces. Some definite data regarding this question would be of real value. As regards their photograph§ of some insulators after exposure to a polluted atmosphere, a more definite test is to place

* Paper by Messrs. B. L. GOODLET, F. S. EDWARDS, and F. R. PERRY (see vol. 69, p. 695).
† "Dielectric Phenomena in High-Voltage Engineering," chap. 2.
‡ "The Physics of Crystals," chaps. 14, 15.
§ Not reproduced in the *Journal*.

similar insulators—some at a potential, others uncharged—in a fog chamber, where the conditions are controllable and can be kept reasonably constant. Comparisons of the weight and nature of the deposit indicate definitely the influence of the electrostatic field. The authors refer to the deterioration of the electric strength of air in confined air spaces. A very important instance of this arises in connection with the thin film of air between two dielectrics, e.g. compound and varnish-paper, in a bushing insulator. There is often very poor adhesion and one naturally assumes that such a film of air exists. This thin film is stressed both radially and axially. The dimensions of bushings are usually based on the wet and dry flash-over characteristics of the outside porcelain surfaces. Assuming that the thin film of air has poor dielectric qualities on account of the fact that it is closely confined, the breakdown voltage for the bushing will depend on the electric strength of that air and not of the air outside. Further, the fact that the bushing has associated with it a radial field of high intensity also tends to reduce the electric strength of the confined air. Turning to the question of the breakdown voltage of oil, the authors remark on the fact that the discharge voltage goes up with an increase of temperature, but they offer no explanation of this. Peek noticed a similar effect and suggested that it was due to the decrease in insulation resistance of the oil with increase of temperature, which would result in more even stressing of the oil and thus increase the critical voltage. When investigating surface discharges the authors made an attempt to measure the length of streamers and to correlate the length with other factors; they are to be congratulated on the remarkable way in which they turned an apparent failure into success. Their explanation of the varying length of streamers is interesting from the point of view that the circuit conditions are not dissimilar to those which hold in the case of an overhead line with polluted insulators. We know that the latter are liable to give rise to surges, but there seems to be some doubt as to the true explanation of these. The remark is made on page 712 that 50-cycle and impulsive discharges are very similar. [Mr. Youatt here exhibited two lantern slides.] These slides show a 3-unit post-type insulator flashing-over under 50-cycle and impulse voltages respectively, and it is clear that there is a tendency for the impulse arc to follow the surface of the insulator. Do the authors think that this characteristic is due to the high-frequency ripple which is nearly always present at the peak of an impulse wave? This preference for an impulse flash-over to follow the surface of the insulator was remarkably demonstrated in another case where a surface some 15 inches in length was in parallel with a gap of $2\frac{1}{2}$ inches. The impulse arc showed a decided preference for the longer path. In discussing the breakdown of solid dielectrics the authors seem to disparage the "simple theory" held by many engineers—that insulators have a certain electric strength and that if this is exceeded the dielectric will break down. There is an analogy in connection with the mechanical testing of materials, where another "simple theory" is held by engineers, namely that the test piece will break down if a certain tensile stress is exceeded, in spite of the fact that it is well known that the ultimate stress is altered by temperature conditions; the same should apply in the case of dielectrics. Further, a good deal of work is being done at present on the mechanical fatigue strength of materials, and although the implications are not thoroughly understood, there is no suggestion that we should depart from the original simple theory that stresses above a certain value will cause breakdown. I suggest that the theory at present held regarding dielectrics should be worked to in spite of the fact that we find variations of temperature, and alternating voltages give results which do not entirely confirm it. In the equations which the authors quote in attempting to develop a thermal theory of breakdown, particularly in that due to Dreyfus (No. 6), after substituting for γ_0 one finds that the breakdown voltage varies inversely with the square root of the frequency. If the frequency is made zero, to represent the case of direct current, the critical voltage rises to infinity. One therefore concludes that all high-tension transmission should be by means of direct current in order that insulation may be dispensed with! Fig. 4 illustrates the effect of a sharp-edged electrode in increasing the breakdown voltage of an air-gap. Peek found that the apparent electric strength of air between two parallel wires varies inversely with the square root of the radius of the wires. It is a reasonable assumption that a similar effect occurs in the type of electrode shown; if so, since the radius of the knife edge is infinitesimally small, the apparent electric strength of air in the knife edge—plane gap will be considerably higher than that in the gap in parallel, which consequently flashes over first. The authors' comments on this tentative explanation of the "paradox" would be of interest.

Mr. E. J. Evans: With reference to the question of the strength of materials, mentioned at the beginning of the paper, when approaching the subject of dielectrics it would appear to be helpful to make use of the mechanical analogy which is frequently valuable in obtaining a bird's-eye view of electrical problems. A machine can be considered to be distinct from a mechanism by virtue of the mechanical properties of its elements. A mechanism can be analysed dynamically, but it does not become a machine until the materials of which it is to be constructed are fixed. In other words, the most important factor in machine design is the strength of the materials of construction. Similarly, in applications of electricity one can analyse electrical circuits and pieces of apparatus without reference to the materials of which they are constructed, but one does not arrive at an actual engineering entity until the property which corresponds to mechanical strength, namely electric strength, is taken into consideration. The similarity is found to be even closer when one remembers that the energy in a circuit is transmitted not by the conductors, but via the dielectric. There appears to be a large amount of data available in regard to electrical breakdown of gases at low pressures and electrical phenomena *in vacuo*. Thermionics, to which so much attention is being devoted at present, is only one branch of the subject of electrical breakdown. Are the lessons which have been learnt by physical and

mathematical investigation of electrical breakdown *in vacuo* and in gases at low pressures being extended to air-gap dielectrics, and thence to the breakdown of solid dielectrics? Is the electrical strength of a solid dielectric affected by the presence of any of the several types of mechanical stress? The authors showed a slide of a flash-over occurring in an air-gap of which one electrode consisted of a cylinder with a sharp edge, and they point out that as a result of the presence of the sharp edge the flash-over prefers to take a path which in effect increases the air-gap to approximately twice its actual value. It seems to me that this striking effect should be capable of considerable application in switchgear design. In the section dealing with high-frequency breakdown the authors state that they use a Tesla coil for producing the high-frequency voltages; are other methods used for this purpose, and are they not preferable to the Tesla coil? The question of high-frequency breakdown appears to be bound up with the subject of boundary conditions in electrical phenomena. The study of boundary conditions is becoming increasingly important in both physics and chemistry, and I should like to know whether the authors consider that the study of the mechanism of electrical breakdown would be materially assisted by concentrating on this question of high-frequency breakdown and its general bearing on boundary conditions.

Dr. H. C. Bowker: I was interested to see in the picture* showing the discharges obtained when using the Tesla coil, that the discharge started by coming straight downwards from the sphere for a short distance (about half the radius) and then branched off at right angles, spreading out in all directions and eventually reaching the earthed electrode. It was pointed out to me some time ago that discharges of this shape often occurred, and that the short, straight "stem" was always associated with the negative electrode.† I should like to ask whether the authors have observed any connection between polarity and discharges of this type. Referring to Fig. 1, have the authors had any difficulty in getting those parts of the curves which correspond to the curve for the discharge from a point? When I was obtaining similar curves myself some years ago, I found that my results differed if I used a different transformer or if I put a resistance in series with the gap. The breakdown voltage seemed to vary with the amount of preliminary discharge, which may have heated up the gas or the electrodes. Again referring to Fig. 1, in connection with the first of the peculiar phenomena which the authors mention on page 698, I should like to draw attention to the fact that halving the gap only reduces the breakdown voltage from about 800 to 700 kV for a 75-cm sphere. The paradox remains, however, and I should be glad to know whether the authors have any explanation of it. I am interested in the decrease in the breakdown voltage after successive applications of the voltage, mentioned on page 701. I also have found that when successive spark-overs take place in a gas occupying an enclosed space this will occur. I found that if I raised the voltage very gently when near the spark-over voltage I could reach a higher value than what appeared to be the normal figure. The resulting spark was usually a very fat one, which seemed to heat up the spheres or gas. The next reading was always low. By allowing a little more time and raising the voltage much more slowly, I was able to get fairly consistent readings. I always noticed this irregularity when working at ordinary temperatures. When I was making tests at a high temperature I found that there was no possibility of getting an extra-high reading, nor could I get the extra-low reading. The results were much more consistent, and, of course, they were in agreement with the average readings at ordinary temperatures.

Mr. R. M. Longman: It is fortunate that the electric strength of air, oil, and high-class insulators, is generally greater for impulse or high-frequency tests than for the standard frequency of 50. It means that carrying out tests at a frequency of 50 gives one the comfortable feeling that for higher-frequency or surge conditions there is a much greater margin of safety. Whilst higher breakdown values are obtained both in air and in oil for spheres and planes than for the point-plane gap, there is unfortunately such a tendency to overlook points in the finished article that for safety the point-plane values must be adopted. The presence of a split pin, as I discovered recently, may alter the flash-over value very considerably. I cannot agree with a previous speaker that the insertion of a knife-edge will probably add to the electric strength, for in general practice the reverse is, I think, the case. From Fig. 15 I deduce that an insulator which may be quite satisfactory as a supporting unit without a central conductor passing through it, will have a much lower flash-over value if used with the same clearances but fitted with a central conductor, e.g. as a floor or wall insulator, or as a terminal insulator on a transformer. The effect of a conductor passing through an insulator also occurs in the tube-type current transformer, and it is interesting to apply a voltage to one of these in the dark and watch where the discharge occurs. I should think that under impulse tests it would be even more interesting. I recently came across a porcelain bushing having a central conductor which was used at approximately 20 kV in oil. It was of the ordinary bellied-type construction with centre fixing flange. The latter was filled with air, the slot in the end washer being at the bottom instead of the top, which effectively kept the air in. In my opinion this arrangement was wrong, and I have therefore had it reversed and the air expelled. Regarding the breakdown of solid dielectrics (pages 715 and 716), I am interested in the concept of thermal balance as expressed by Miles Walker. It is very similar to that put forward by Mr. Law many years ago when he spoke of the life of electrical machinery as consisting of so many temperature-hours above a certain critical temperature. The life of an electrical machine depends on its insulation resistance, and if it is overheated either by dielectric stressing or by purely thermal stress, its life is seriously affected. The authors refer (page 721) to the mechanism of real electrical breakdown of solids, but I think they are quite correct in dwelling so much upon thermal instability; after

* Not reproduced in the *Journal*.

† T. TERADA, U. NAKAYA, and R. YAMAMOTO: "Experimental Studies on Form and Structure of Sparks," *Scientific Papers of the Institute of Physical and Chemical Research, Tokyo*, 1930, vol. 13, p. 207.

all, have we in practice any perfect solid dielectrics? Glass and porcelain are the ones which most nearly approach the ideal. We have to make the best of, and know the worst of, the solid insulating materials with which we have to work, and we are always hoping and striving for something better. As regards Tables 13 and 14, may not the greater electric strength in oil be partly due to better heat conduction as well as to elimination of air? The authors deal at some length with the electric strength of fibrous materials, pressboard, and bakelite. My own experience of the breakdowns of bakelite is that they are due without exception to faults in manufacture—either through the laying-on of the paper or the bakelized powder. In one case the bushing was built up on a slightly smaller-diameter rod, and this allowed small air spaces to be formed, resulting in the failure of all the bushings made in that manner. In another case, after a breakdown a slight separation was found between layers after about one-eighth of the bakelite had been removed. The authors emphasize that it is of no use increasing the length of bushings without regard to their thickness. Designers and those who specify terminals should bear this in mind. A long thin procelain bushing is not satisfactory.

Mr. R. D. Ball: I should like to ask whether the authors have investigated the effect of a directed air-blast on the spark-over voltage between electrodes in air. By this means it may be possible to replace the ionized air by neutral air, and if the breakdown action is slow there is a chance of raising the breakdown voltage for a given gap setting. If the breakdown action takes place at the velocity of light, however, there is of course little chance of the breakdown voltage being raised. Experiments in this direction might yield useful information regarding the question of the rate of ionization and formation of corona.

Mr. W. R. T. Skinner: The figures given in Table 3 do not agree in all cases with the points plotted in Fig. 12. Which is correct, the table or the figure?

Messrs. B. L. Goodlet, F. S. Edwards, and **F. R. Perry** (*in reply*): The points raised by the various speakers will be dealt with according to the subject matter of their remarks.

(1) *Phenomena With Alternating Voltages of Normal Frequency.*

(*a*) *Air Breakdown at Large Spacings.* The explanation of the apparent discrepancy between the calculated gap setting at which the discharge-voltage and breakdown-voltage/distance curves begin to diverge, to which Prof. Wheatcroft refers, is that, although according to Peek* the divergence starts for a gap of $2r$ between spheres, the difference is not noticeable to an observer until the gap is considerably increased. According to Peek again, corona is not actually visible between two spheres until the spacing is equal to $8r$. The curves in Fig. 1 are seen to diverge at gap settings varying from about 6 to 7 times the sphere radius, though this is for the sphere-plane gap. We do not consider it safe to assume that from considerations of symmetry the field between two spheres is unaffected by the insertion of a plate at a potential midway between those of the spheres, in the region where brushing occurs before spark-over. Klemm* gives tables showing the starting point of discharges for sphere-sphere and sphere-plane gaps, for spheres up to 8 cm in diameter. In all cases the starting voltage for a sphere-plane gap is more than 50 per cent of the starting voltage for a sphere-sphere gap set at twice the spacing. The smallness of the scale of the illustration also prevents the beginning of the deviation from being shown clearly. Incidentally, the dimensions given in Fig. 1 are those of the sphere diameters, not the sphere radii. They affect Prof. Wheatcroft's figures, increasing, however, the discrepancy to which he refers.

Mr. Youatt has similarly assumed the dimensions to be radii, so that his value should be 7·4 instead of 3·7. His statement that the curve for the point-plane gap follows the critical spacing/voltage curve for the sphere-plane gap is not quite accurate, but we agree that the difference is not very marked.

The theory, so commonly applied to concentric conductors, that corona enlarges the diameter of the smaller electrode and so reduces the stress if the ratio R/r is above a certain critical value, while true to some extent is not an accurate representation of the conditions in a discharging sphere-gap, as the boundary of the discharge is highly irregular in shape, with numerous pointed projections.

In reply to Dr. Bowker, no difficulty was experienced in obtaining the breakdown curves at the larger spacings, but we can well understand that he obtained different results with different transformers or different series resistances. The most reliable results, which correspond with service conditions, are those where a transformer of large output and low reactance is used.

Mr. Youatt's suggestion regarding the fouling of insulators has been anticipated.†

We agree with him that air pockets may occasionally be found in outdoor bushings between the compound filling and the paper, or between layers of paper, but the danger does not lie in the confined space. This may be an advantage, as the supply of oxygen is thereby strictly limited. Also, thin films of air have a considerably higher electric strength than is obtained with thicker films. The risk of axial breakdown is greatly increased by the presence of air pockets, but the designed normal axial stress at the test pressure is usually less than the stress required for air breakdown. During a dry spark-over test, however, there would be some risk of internal spark-over on a badly manufactured outdoor-type bushing. We agree with Mr. Longman that air spaces between the paper layers are a prolific source of trouble.

Regarding Fig. 4, Mr. Youatt quotes Peek with approximate accuracy as saying that the apparent electric strength of air between parallel wires varies inversely as the square root of the radius of the wire, and proceeds to the limit for $r = 0$, whence the apparent electric strength is infinite. It must not be overlooked, however, that although as the radius decreases, the electric strength increases, so does the stress, and the breakdown

* F. W. Peek: "Dielectric Phenomena in High-Voltage Engineering," 3rd edn., p. 68.

* A. Klemm: *Archiv für Elektrotechnik*, 1923, vol. 12, p. 553.

† B. L. Goodlet: *Journal I.E.E.*, 1929, vol. 67, p. 1177; also B. L. Goodlet and J. B. Mitford: *Report of the International Conference on Large Electric Systems*, 1929, vol. 2, p. 389.

voltage may therefore decrease with decreased radius of wire.

Dr. Bowker's remarks on breakdown in confined air spaces are very interesting.

In reply to Mr. Ball, we have not investigated the effect of a directed air-blast on the spark-over voltage between electrodes in air. Nishi and Ishiguro* found that an appreciable increase in spark-over occurred due to air flow, the effect being more pronounced at low than at high frequencies.

(*b*) *Oil Breakdown at Large Spacings.* In reply to Mr. Skinner's query, Table 3 is correct. We regret that one of the points in Fig. 12 was mis-plotted.

(*c*) *Surface Discharges in Air and Oil.* Mr. Longman's remarks on the proportioning of bushings and the futility of increasing one dimension, say the length, without regard to the laws governing the behaviour of bushings, emphasize the need for a sound knowledge of the laws of surface discharge.

(2) *Phenomena with Impulsive, High-Frequency, and Continuous Voltages.*

We agree with Mr. Youatt that there is sometimes a tendency for an impulse spark to follow the surface of the insulator more closely than a 50-cycle spark, and that this may be due to high-frequency ripples at the peak of the impulse wave. Other causes, however, contribute to the appearance of the spark. The polarity of the impulse has an effect; a positive impulsive discharge takes the direct air path, while a negative impulse causes a discharge which clings more closely to the insulator, even when no high-frequency ripple is present in the wave.

In reply to Mr. Evans, the Tesla coil is the most satisfactory method of producing damped high-frequency voltages. Equipment producing undamped oscillations is perhaps easier to work with, but does not correspond to service conditions.†

The question of polarity does not, of course, arise in high-frequency damped oscillatory discharges.

As Mr. Longman remarks, it is very fortunate that the electric strength of air, oil, and solid insulation is generally greater for impulsive and high-frequency voltages than for 50-cycle voltages, because the voltages impressed as a result of lightning and switching disturbances are also higher, so that the true factor of safety is not increased as much as the test figures indicate.

(3) *The Breakdown of Solid Dielectrics.*

In reply to Prof. Wheatcroft, on account of limitations of space we were unable to include as many experimental results as we should have wished, but Fig. 31 may be taken as typical of the correlation which exists between the power factor and breakdown voltage of varnish-paper tubes.

We cannot agree with Mr. Youatt that there is any real analogy between mechanical and electrical breakdown (see Appendix II). As stated in the paper (page 715), there is some evidence that at low temperatures the form of the electric field plays a predominant part in determining the breakdown voltage, to the almost complete exclusion of effects such as time of stressing and temperature; but this ceases to be the case at higher temperatures. If we have understood Mr. Youatt aright, he suggests that we ought to obtain the same breakdown stress on a thick sample as on a thin one, i.e. the breakdown-voltage/thickness curve should be a straight line through the origin of co-ordinates. This is rarely even approximately true for cold materials, however, and it ceases entirely to have any validity for hot materials. In fact, as equations (7) and (8) lead one to expect and experience proves, the breakdown-voltage/thickness curve departs very widely from a straight line through the origin.

Mr. Youatt's statement that there is no suggestion that we should depart from the original simple theory of breakdown due to the stress exceeding a certain figure, is therefore hardly correct. Why, if the maximum-stress theory is correct, are d.c. breakdown figures sometimes two or three times as high as the peak values of the corresponding 50-cycle a.c. breakdown figures? The same speaker's deduction from equation (6) is invalid as he assumes that p_0 is proportional to the frequency, which is not necessarily the case, particularly at very low frequencies. p_0 is not zero, even with continuous voltages. Other factors also begin to operate with d.c. voltages which can be neglected in comparison with the much larger effects associated with alternating voltages.*

Mr. Evans inquires regarding the effect of mechanical stress on electric breakdown. The breakdown strength of insulating material always decreases with increasing mechanical tension, the change being quite small until the material is damaged by the mechanical tension, when the decrease becomes more rapid. The tests specified in B.S.S. 419—1931 ("Varnished Cloth, Sheet Strip or Tape for Electrical Purposes") and B.S.S. 137—1930 ("Porcelain Insulators for Overhead Power Lines") recognize this fact.

In quoting Mr. Law's statement that the life of electrical machinery consists of so many temperature-hours above a certain critical temperature, Mr. Longman seems to be confusing thermal stability and deterioration. This point has already been dealt with in our reply to Dr. Miller.† Nor do we agree that the life of an electrical machine depends on its insulation resistance, unless this term is being used in a much more general sense than its strict technical meaning warrants. Regarding Tables 13 and 14, the greatly improved breakdown voltage of paper and pressboard after oil-impregnation is attributed to the displacement of air, though no doubt the better heat conduction and heat capacity of oil have an effect on the tests at 50 cycles per sec. Under impulsive voltages, however, this explanation ceases to be tenable.

* *Bulletin of the Institute of Physical and Chemical Research, Tokyo*, Oct. 1929, p. 95.
† *Journal I.E.E.*, 1931, vol. 69, p. 1177.

* See *Journal I.E.E.*, 1931, vol. 69, p. 726, References 12–19.
† *Journal I.E.E.*, 1931, vol. 69, p. 1178.

THE SELECTIVITY OF BROADCAST RECEIVERS.

By PROF. C. L. FORTESCUE, O.B.E., M.A., Member.

(*Introductory remarks to a Discussion before the* WIRELESS SECTION, *24th February*, 1932.)

(1) *Introduction.*—The electromotive forces in the aerial of a broadcast receiver are of infinite variety. Even those arising from the transmitting station to which it is tuned have a considerable range of frequency, within which range there are also undesired components arising from other transmissions and from natural causes. The different elements of the receiver have different functions, but, considered as a whole, its duty is to convert the incoming signal into audible sound, the intensity and frequency of which is related in some manner to the variations of the electromagnetic waves radiated from the transmitter. The selectivity of the receiver may be described as the extent to which the output of sound is independent of the waves emitted from all sources other than the transmitter from which the desired programme is being received.

(2) *What range of audible frequency is desirable?*—The first question arising in connection with the selectivity is the extent to which the sound output should be a replica of the modulation of the waves radiated from the transmitter. If the output is not an exact replica, what deviation is permissible or desirable, and under what conditions?

Many analyses of sound have been attempted and, as the apparatus becomes more and more sensitive, components of higher and higher frequencies are found. The female voice is known to have components with a frequency of 10 000;* and footfalls, hand-clapping, and the operation of typewriters are observed to have components of frequencies approaching 16 000. Provision is not usually made in broadcast transmitters for so great a range, and the vast majority of receivers have a much more limited range. A lower frequency limit of 50 and an upper limit of 5 000 are considered to give good results. But where audio-frequency output is subjected to the most careful scrutiny, i.e. in the production of talking films, it is noticeable that the tendency is to exceed this limit and to provide a full response up to 10 000 cycles per second.

It is, however, not only the limiting frequency that is involved; there is the even more difficult question of the uniformity of response essential for good results. A highly trained observer—not necessarily "musical"—may detect at particular frequencies accentuations, or the reverse, which the ordinary person would not notice. "Musical" people are sometimes even the least critical of all in this respect, owing to their peculiar power of imagining all the missing parts; just as in an ordinary telephone conversation the listener himself provides anything up to 50 per cent of the intelligibility.

No answer to these questions can be satisfactory unless it is given in terms of quantities capable of reasonably exact measurement. What shall be the quantities, how shall they be measured, and what shall be the specified limits in each case? In my opinion some arbitrary maximum frequency-range of, say, from 50 to 10 000 should be taken, and at least two figures of merit should be used to characterize the receiver, viz.—(*a*) a figure giving the area of its response curve as compared with the ideal; and (*b*) a figure representative of the uniformity of response over the active range of frequency. In each case the response must of course be measured in actual sound intensity from the loud-speaker for a given high-frequency input.

(3) *Why do these considerations determine the selectivity of the receiver?*—The rigid logic of the mathematician confirming the experience of the most careful observers shows that the modulated incoming signal may be analysed into an infinite series of harmonic components.* The frequency of these components is distributed above and below the frequency of the unmodulated transmitted wave over a range which is equal to the range of the audible frequency sound that is being transmitted. The unmodulated wave is the familiar "carrier wave," and the harmonic components are the "side-bands." This analysis applies not only to wireless telephone transmission but also to "spark" signals and to atmospherics. In the receiver itself the high-frequency characteristics, the behaviour of the rectifying device, and the "tone correction" in the audio-frequency amplification stages, may be made to combine with the properties of the loud-speaker in any desired way. The properties of all the constituent parts are well known or can be determined experimentally,† and generally there are means for the adjustment of these characteristics when the receiver is in use. For the given receiver with a given adjustment, however, each side-band component gives rise to a sound output, the fundamental frequency of which is equal to the difference between the frequency of a side-band component and that of the carrier wave. This is true whether both side-bands are transmitted or only one; it is also true for any form of detector and whether or not the tuning of the receiver corresponds exactly to the carrier wave. These factors only influence the amplitudes of the fundamental and harmonic components of the sound output. It follows, therefore, that if when receiving the carrier wave of the desired transmission a component of the same frequency as that of a side-band, but from some other transmission, impinges upon the receiving aerial, the results must be the same as if this wave had been a side-band of the desired transmission. In other words, of the infinite number of waves striking the receiving aerial at the same time as the signals from its own transmitter, all must contribute to the sound output in the same way as the

H. FLETCHER: *Bell System Technical Journal*, 1931, vol. 10, p. 349.

* "Encyclopædia Britannica," 14th edn.; H. LAMB: "Dynamical Theory of Sound," 2nd edn., p. 89; C. R. BURCH and J. BLOEMA: *Philosophical Magazine*, 1925, vol. 49, p. 480; and L. J. PETERS: *Transactions of the American I.E.E.*, 1926, vol. 45, p. 581.

† C. L. FORTESCUE and F. RALPH: *Journal I.E.E.*, 1930, vol. 68, p. 883.

corresponding side-bands contribute. Since only the side-bands of a limited range produce audible results, it follows that only the interfering waves within this range will become audible (unless these waves include both carrier waves *and* side-bands of an undesired programme). The greater the range of side-bands for which provision is made, therefore, the greater will be the range of interfering components also included. Is it not thus beyond question that the limit of selectivity of a broadcast receiver is solely determined by the range of audible-frequency notes for which it is designed? And is not any denial of this tantamount to endowing the receiver with some imaginary quality enabling it to examine incoming waves of a given frequency and to say " This one is mine, that is not "?

(4) *Are receivers as selective as possible?*—There is a good deal of evidence that many receivers accept high-frequency energy over a far wider range of frequency than is necessary, with the result that they suffer from serious interference, both the side-bands and the carrier waves of transmissions on neighbouring frequencies being received and their programmes heard. Such receivers are unbalanced in the sense that high-frequency components are received over a far wider range of frequency than is reproducible in the audio-frequency stages or in the loud-speaker. For instance, a receiver tuned to a high frequency of 10^6 ($\lambda = 300$ m) may respond to the extent of perhaps 30 per cent to frequencies which are 50 000 above and below this central value, and yet the loud-speaker may be limited to a frequency only just above 2 000. It would obviously be more satisfactory to limit the high-frequency range to 30 per cent at a departure of, say, 5 000 cycles per second from the central frequency. The needs of the loud-speaker could still be met and the energy received from other transmissions would then be negligible.

(5) *What is the best circuit arrangement for obtaining the necessary selectivity?*—The ideal high-frequency response curve would, no doubt, be a rectangle covering a range of 10 000 or 12 000 cycles per second on either side of the frequency of the carrier wave. But this can only be realized to within a few per cent by means of a complicated filter, which is both expensive and difficult to adjust if provision is to be made for more than one wavelength. A two-coupled circuit with its double-humped response curve can be made to give a fair approximation, but it involves tuning two circuits and adjusting the coupling to give the best results. Some reaction may also be necessary. A single circuit of high decrement can easily be made to give practically a uniform response over the required frequency range, but, as already mentioned, is subject to unnecessary interference. There seems, therefore, to be no way of obtaining the ideal characteristic on the high-frequency side alone that is not open to objection. The simplest arrangement is undoubtedly the single resonant circuit, but when the decrement is sufficiently low to avoid interference by transmissions on adjacent wavelengths, the higher-frequency side-bands of its own programme are themselves seriously reduced. Audio-frequency correction in the same sense thus becomes necessary on account both of the high-frequency effects and of the characteristics of the loud-speaker. It may be reasonably easy to accomplish one of these corrections without undue complication, but is it possible to compensate satisfactorily for both of them? Alternatively, since the loud-speaker causes the most serious errors, is it not possible so to reduce the decrement of the high-frequency circuit that interference is relatively slight, and, in doing so, to reduce the high-frequency side-bands only to such an extent as will result in the errors being small compared with those of the loud-speaker? This aspect of the selectivity problem thus seems to depend mainly on the loud-speaker. When its errors are reduced, the correction for the shape of the resonance curve will be more important.

(6) *Can the average purchaser of a broadcast receiver be entrusted with a sharply-tuned high-frequency circuit?*—This is a matter admitting of no mathematical treatment, and it is wholly outside the realms of any logical argument known to me. The results of experience in this direction, not only of the users of expensive receivers but also of the much larger number of people who have the simpler and cheaper instruments, would be very valuable.

(7) *Would the general use of selective receivers enable the difference of wavelength between transmissions to be reduced?*—In view of the facts set out above, it must be concluded that there are neither theoretical nor experimental grounds for any hopes in this direction. For morse signalling at hand speed, yes! for the range of side-bands for which provision is necessary is quite small. For broadcasting, however, the problem is different. Even the possibility of using only one side-band is not promising—it complicates the correction, and the insertion of the carrier wave at the receiver is quite impracticable. In fact, any tendency that may be observable is in the direction of a wider spacing in the frequency spectrum rather than the reverse.

Discussion before the Wireless Section, 24th February, 1932.

Mr. N. Ashbridge: Since the selectivity of receivers is closely associated with the performance of broadcast transmitters, the subject of selectivity is of great importance to the British Broadcasting Corporation. The first question I wish to discuss is the demand for selective receivers on the part of the public. We may divide the public into two classes: in the first class there are those who live in an area of strong field strength of upwards of 20 millivolts per metre, where selectivity is not particularly necessary because very little interference from other sources is noticeable. In the second class there are those who live in an area where the signal strength is about 5 millivolts per metre, and who might reasonably expect good reception were it not for interference due to peaks of signal strength from a distant station at night. At times the two stations may be of equal field strength and only 9 kilocycles per sec. apart in frequency. It is often suggested that the B.B.C. ought to cut off the higher frequencies at the transmitter. Apart from the effect that the adoption of this suggestion

would have on what we call "side-band heterodyning," if we were to cut off at, say, 5 000 cycles per sec. the masses of people living in areas of strong field strength would have reason to complain of the inferior quality of the transmissions. In this connection one has to consider what frequencies from the interfering station cause the "grasshopper" kind of noise which we call side-band heterodyning. I think this noise is due not to the extremely high frequencies but to those where the energy is the greatest, i.e. frequencies of 1 000 to 2 000 cycles per sec. It is therefore questionable whether, if the higher frequencies were deliberately cut off in the transmitter, there would be much reduction of these noises. With regard to highly selective receivers, one of the first essentials is stability of tuning. Unless care is taken in the design of a mains receiver the tuning will vary with every change in the mains voltage. Even in the case of transmitters a greater degree of stability is desirable if we are to use the extreme degree of selectivity which has been discussed lately. Prof. Fortescue has stated that the range of musical frequencies which ought to be included is 50 to 5 000 cycles per sec., and although I am in agreement with him here I consider that sooner or later higher frequencies will have to be considered. Recording by the "hill and dale" method in America deals with frequencies up to about 9 000, and this may tend to accentuate the demand for higher frequencies. On the other hand, a large number of our programmes are transmitted over Post Office circuits, some of which cut off at just over 6 000 cycles per sec., and of course this prevents the transmission of the higher frequencies in some cases. With regard to the judging of quality by musical people, we notice that a musician, no matter how good he may be, is not particularly sensitive to the width of the frequency band included in the transmission. He is, however, very sensitive to changes in amplitude, i.e. bad modulation control. On the other hand, people who are not musicians but who are interested in musical reproduction will at once notice if one cuts off frequencies above 5 000 cycles per sec. I believe this class of listener is very numerous nowadays. The public in general do notice the difference between the frequency cut-off of 5XX and that of the new transmitters. Even at 5 000 cycles per sec. the response of 5XX is reduced by at least 8 or 10 decibels. In addition, many receivers cut off seriously on the long wavelength employed by 5XX. As regards the upper limit for loud-speakers, I think 2 000 cycles per sec. is rather pessimistic for the average receiver in use to-day. Many modern loud-speakers register well above 5 000 cycles per sec., and although the response may be hopelessly non-linear at this frequency the fact that some sound is produced is more important than the maintenance of an exact mathematical relation to the response at other frequencies. Turning to the question of the spacing which should be allowed between the frequency channels of broadcasting stations, I should like to draw attention to the fact that the London Regional transmitter works at a frequency which differs by 11 kilocycles per sec. from that of its troublesome neighbour, and the frequency of the North Regional transmitter is roughly 11 kilocycles per sec. different from those of the Langenberg and Prague stations. Because these are free from interference, however, it is not necessarily correct to say that the present standard spacing of 9 kilocycles per sec. is quite adequate. We are very interested in single side-band working, i.e. transmitting one side-band with the carrier but not the other. To derive any considerable advantage from this system one would presumably have to cut off one side-band in the receiver. If the whole of Europe decided to change over to single-side-band working (and one day they may do so), each of the 12 million licensed receivers in Europe would have to be provided with a filter which would cut off one side-band completely. Such a filter could certainly not be produced for less than £1, and therefore, apart from the technical difficulties, the change-over to the new system would be exceedingly costly. Finally, I want to say something about the position abroad with regard to the frequency separation between stations. Many broadcast engineers abroad are not very concerned about frequencies over 4 000, and the type of receiver which they consider suitable for working in a country district is designed to cut off almost completely at 4 000 to 4 500 cycles per sec. in order to give interference-free reception. Foreign radio engineers do not complain of side-band heterodyning from our stations, whereas in England we get numerous complaints of side-band heterodyning even when there is an 11-kilocycle separation. There are two reasons for this state of affairs. In the first place, ultra-selective receivers are used abroad, and secondly (this is much more important) other countries employ a much higher mean modulation than we do. Modulation records which we have taken recently on certain Continental stations show that their mean modulation may be double ours. I consider that in the future there will be a demand for higher modulation frequencies: we should be able to receive on a loud-speaker much higher frequencies than 4 500 or 5 000, and I therefore feel that we must seriously consider the question of a wider frequency separation between stations. In this connection it is interesting to note that the United States consider that the broadcast cables now being put down should have a linear response up to 8 000 cycles per sec.

Mr. P. K. Turner: Prof. Fortescue makes the implication that the talking film sets a higher standard than broadcast reception in the matter of the upper frequency limit, whereas my experience of both gramophone recording and talking-film making, and, from the receiving end, of broadcast transmission, proves to me that the reverse is the case. My experience is that a clear cut-off at 5 000 cycles per sec. is regarded as a luxury in gramophone or talking-film recording, whereas we know that broadcast transmission contains at least another octave above that frequency. Prof. Fortescue is of opinion, and in strict logic I think he is perfectly correct, that in any attempt to estimate the performance of radio receivers one must include the performance of the loud-speaker. Unfortunately the practicability of this is very doubtful, because even if one includes in the performance curve of the receiver the mean spherical radiation of the loud-speaker, one cannot make any allowance for the acoustic circumstances in which it is being used. It is not only that the set must include one particular loud-speaker and no other, but it must be used in one particular type of room and no other; otherwise the

curve cannot be guaranteed. A sounder procedure is to base all our considerations on getting the best possible receiver, and to leave as a separate problem the selection of the best loud-speaker by suitable impedance matching. Again, according to Prof. Fortescue, strict mathematical logic implies that if a stray side-band from an unwanted transmission cuts into the band we are trying to receive, the results must be the same as if this wave had been a side-band of the desired transmission. I am not entirely convinced about this, because there is the difference that what we wish to receive consists of two side-bands, on each side of the carrier and having a definite phase-relation with it, whereas the unwanted radiation consists of one side-band only, its carrier and other side-band being possibly cut out by the receiver. Therefore we cannot say that the stray side-band must necessarily be identical in behaviour with the wanted pair of side-bands. An interesting point in this connection is the "demodulation" effect, i.e. the fact that the modulation of the unwanted carrier tends to disappear when the signal strength of the latter has been reduced to not more than 1/100 of that of the wanted carrier. I have found by experiment that when a carrier 10 kilocycles per sec. from the desired transmission is reduced to 1/300 or 1/400 of the signal strength of the wanted carrier, and the audio-frequencies are then reconstituted by means of a differentiating circuit, the "grasshopper effect" is reduced to very small dimensions. In a circuit of that kind the actual carrier, the heterodyne 10-kilocycle whistle, is reconstituted at full strength and has to be dealt with specially; but this presents little difficulty. I should like to press very strongly for the retention of frequencies above 5 000 cycles per sec. There is no doubt that anyone who has a keen (but not necessarily musically trained) ear and who is not deaf to those frequencies, soon learns to appreciate the difference between a transmission with them and one without. I find that even musical people are at first satisfied with transmissions which do not contain either these frequencies or those below 100 cycles per sec., and which suffer from all sorts of defects. They sub-consciously supply what is missing and they also dispense with what ought not to be there. However, if such people hear in quick succession a good and a comparatively poor transmission, they soon learn to notice the difference and become dissatisfied. In my opinion 8 000 cycles per sec. is the lowest cut-off possible if first-class quality is to be obtained. Lastly, I should like to state that there may be difficulties as to the handling of extremely selective sets by unskilled people. First, the mechanical difficulty of adjusting to exact tuning is merely a matter of gearing. Secondly, there is the difficulty of knowing when the set is correctly adjusted—a much more difficult problem. Receivers of the kind which I have been discussing, in which a super-selective circuit is followed by tone correction, give extraordinary results if there is any error in tuning. If the set is 200 cycles per sec. off tune, strong resonance is obtained at 200 cycles per sec. and nothing at all at lower frequencies. It is therefore essential to provide some indicating device, so that the listener may tune in by adjusting until the needle on the indicator goes up and comes back again, instead of relying on his own ear.

Mr. F. S. Barton: With regard to the remarks which have been made as to the necessary frequency range, I should like to refer to some work carried out in the Bell Telephone Laboratories which has recently been published* in America. In these tests, while several experienced listeners were listening to an orchestra the low and high frequencies were cut off by varying amounts with filters. It was found that when a frequency range extending from 80 to 8 000 cycles per sec. was employed the listeners considered the reproduction to be 95 per cent perfect. The problem before the designer of a commercial radio-telephony channel is simpler than the broadcast problem, because the designer knows definitely what band he has to deal with and he has not to arrange the apparatus so that it may be operated by a layman. Further, he is not hampered by financial considerations, because increasing the cost of a commercial receiver by £50 only adds a trifle to the capital outlay on the whole channel, and if the more expensive receiver gives an improved performance it will soon show an economic return. The increasing congestion in the short-wave channel makes it necessary to use that channel as efficiently as possible, and this can best be done by means of stable transmitters and very selective receivers. At the Royal Aircraft Establishment at Farnborough we are faced with the problem of obtaining short-wave communication for the Royal Air Force despite the inroads of commerce, and in order to solve this problem we are trying to design more selective receivers. Our ultimate object is to produce receivers suitable for aircraft work, but we usually approach an aircraft problem by first considering the same problem as applied to ground communications. Inspired by the work of the Post Office Research Station at Dollis Hill, we decided to investigate the possibilities of a super-heterodyne receiver with a band-pass filter in the intermediate-frequency amplifier. By a band-pass filter in the intermediate-frequency amplifier I mean a filter designed on the Campbell and Zobel theory and working between definite impedances, and not the arrangement of two coupled circuits arranged to maintain their coupling substantially constant over the tuning range, to which the term "band-pass filter" has been wrongly applied by the broadcast receiver manufacturer. While the latter arrangement is an improvement on a single circuit, and also on a coupled circuit with adjustable coupling, it is not a band-pass filter in the strict sense of the term. I cannot understand why band-pass filters have not been more used for radio frequencies, and I should be glad of information regarding the operating characteristics of this type of filter.

Mr. M. G. Scroggie: It may clarify our ideas on the subject of the relationship between selectivity and the desirable band of audio frequencies, to refer to three practical cases. In the first case the two transmissions are completely separated and the side-bands do not overlap at all. It is universally agreed that, at any rate in theory, it is possible to separate these transmissions completely in the receiver by using a perfect band-pass filter. In the second case the side-bands overlap, and there seems still to be some controversy over the question

* W. B. Snow: *Journal of the Acoustical Society of America*, 1931, vol. 3, p. 155.

whether it is possible to obtain the whole band of frequencies due to one of the stations, at the full modulation without any heterodyne interference. In the third case the side-bands overlap the carrier waves; it is now, I think, generally agreed that it is impossible to receive one of these transmissions without interference except by losing some of the modulation. The orthodox position is that complete separation is possible only in the first case, and, as Prof. Fortescue points out, it is generally considered desirable to cover an audio-frequency band of 10 kilocycles per sec., or preferably even more. What I have great difficulty in understanding is how it is possible to reconcile these aims with the unpleasant fact that the frequencies of stations are at present, on the average, separated by 9 kilocycles per sec. It seems to me not very much use discussing, at length, principles which can have no actual application to things as they are, but which can only be applied in things as we should like them to be. Assuming the principles stated by Prof. Fortescue, even with a theoretically perfect receiver one can cover an audible range up to only 4 500 cycles per sec. In the second case to which I referred, if one tried to include an audio-acceptance up to 10 kilocycles per sec. one would include not only the wanted station but also the carrier waves of two other stations and side-band frequencies of four other stations. To obtain complete freedom from interference the highest audio frequency put out by broadcast stations and received must not exceed 4 500 cycles per sec. with theoretically perfect apparatus; which means in practice that a good receiver can be allowed to reproduce up to perhaps 3 500 cycles per sec. Only those who claim to be able to discriminate between two waves of the same frequency can indulge in any higher hopes than these. If the unwanted station puts out modulation up to 9 kilocycles per sec. it seems theoretically impossible to receive anything at all of the wanted transmission without interference. I think it would be useful if the broadcasting authorities stated exactly what the limits of audio-frequency modulation are. Even if it is possible to discriminate between wanted and unwanted side-bands it is quite idealistic to think of accepting audio frequencies up to 10 kilocycles per sec., for this value includes the neighbouring carrier wave. It would therefore be helpful to know whether it is considered better to cut off at 3 000 or 4 000 cycles per sec. in receivers of practical design, or to tolerate the interference. I would add that there are districts in this country where the field strength from the nearest British station is considerably lower than that from Continental stations, and therefore one cannot assume, even for "local-station" reception, that the field strength of the wanted station is very much greater than that of the unwanted station.

Mr. I. J. Cohen: I should like to give a rough picture of the existing conditions in commercial radio-telephony. Consider, in the first place, the long-wave transatlantic telephone service, which operates on the single-side-band suppressed carrier system. As the circuits are required for telephone use, only the frequencies corresponding to the audio-frequency band of from 250 to 2 750 cycles per sec. are considered. Over this range the response characteristic of the receiving system has to be flat to within ±1 decibel. At present there are not many long-wave telephone circuits, so that there is no necessity to guard against interference from this source. The ether is full of long-wave telegraph transmissions, however; at 250 cycles per sec. from the carrier frequency on one side of the allotted telephony band and at 500 cycles per sec. from it on the other, there exist strong telegraph carrier frequencies. These spread slightly, the degree of spreading being dependent on the nature and speed of keying, and therefore the cut-off of the telephony receiver must be extremely sharp. As to the relative strengths of the wanted and unwanted frequencies, the field strength of the American signals may be as low as 1 microvolt per metre (the usual figure being about 25 microvolts per metre), and that of the telegraph stations about 100 microvolts per metre. An attenuation of 40 decibels is, therefore, required to bring the signals to equal strength, and then to make the telegraphy nearly inaudible another 40 decibels or more have to be added. Thus at least 80 decibels cut-off is required at 500 cycles per sec. from the edges of the received band. In this case, therefore, the ideal rectangular overall frequency characteristic mentioned by Prof. Fortescue is almost a necessity, and I maintain that such a characteristic can be obtained only with properly designed band-pass filters or their equivalent high- and low-pass sections. Referring to the multiple-detection type of receiver, provided that the early stages are properly protected against the image side-band, the intermediate-frequency band, and overloading, there can be little doubt that the overall curve of the super-heterodyne type of receiver can be made to approach the ideal characteristic more closely than the curves of other types of receivers. On the wavelengths from 14 to 40 metres conditions are now nearly as bad as on the broadcasting band. It is necessary to limit the receiving band widths of the short-wave telephony sets to between 8 000 and 9 000 cycles per sec., and to have a large degree of attenuation outside this range. The Post Office receivers used on these services contain some two dozen valves, five high-frequency tuned circuits, intermediate-frequency band-pass filters containing many sections, audio-frequency filters, and equalizers. To obtain sufficient selectivity it will perhaps be necessary to build the broadcasting receiver of the future on these lines.

Mr. P. W. Willans: One of the principal difficulties associated with a scientific treatment of selectivity problems is, as Mr. Turner has pointed out, our ignorance of the performance of loud-speakers. The acoustic problem involved in the complete circuit of transmitter and receiver comprises the polar characteristics of both the microphone and the loud-speaker, and the acoustic characteristics of both the transmitting and the receiving rooms. These considerations prevent us from taking a strictly scientific view of the subject; broadcasting is an art, not a science. We have to envisage the performer not as playing in the studio and being reproduced as faithfully as possible, but as playing in the home of the listener through the transmitting and receiving systems, which are in effect a part of his instrument. While scientific considerations are invaluable for indicating what is going on, the ultimate criterion must be one of æsthetic value. In any event it seems clear that no

precise quantitative definition of acoustic response is possible and that, in consequence, there is no satisfactory answer to Prof. Fortescue's first question. My second point is more particularly concerned with transmission. I believe that, in view of the nature of present-day broadcast transmissions, Prof. Fortescue's rectangle is not the most desirable response characteristic for a receiver. Most microphones, including the condenser and carbon types used by the B.B.C., give a rising characteristic in the neighbourhood of 3 000 cycles per sec. In the case of condenser microphones this rise in response may amount to 12 decibels at 3 000 cycles per sec. as compared with the response at low frequencies, if the sound is normally incident on the diaphragm. For random incidence this "top" accentuation will not be so heavy, the corresponding rise in response for a condenser microphone being about 7 decibels. As a result of some experience obtained in adjusting the response characteristic of a sensitive receiver, I am fairly certain that the present transmissions are in general too "toppy," and that a receiver designed to have a flat band-pass characteristic will be incorrectly adjusted for best results. I believe it is possible to cut out the higher frequencies without detriment to quality, and this is the only way in which the problem of lessening carrier-wave interference can be tackled. My only fear is that the B.B.C., realizing the situation, may suddenly decide to transmit on a flat response characteristic, in which case listeners would probably find their reproduction lacking in "top." I hope that the B.B.C. will pursue their investigations into the subject of microphones, with a view to eliminating sound-field effect and producing an exact translating device, and that they will consider accentuating the upper frequencies so as to aid in the solution of the selectivity problem at the receiver. Turning to the question of the desirable frequency range in receivers, I regard an upper limit of 5 000 cycles per sec. as more practical than one of 10 000 cycles per sec. Whatever is ideally desirable, we must face the realities of the situation; these are the present state of the ether and of public demand. If the public demands to listen to foreign stations—and a strengthening of this demand is a natural consequence of the increase in the field strength from these stations—the manufacturer is obliged to face the problem of removing the present conditions of severe interference. In actual fact the frequency separation between stations is not as great as 9 kilocycles per sec., since heterodyne notes of 3 000 cycles per sec. or less are often encountered. The only hope of solving the problem of heterodyne interference lies in increasing the strength of our own side-bands; the degree of selectivity necessary to give correct response at the receiver will then at the same time reduce the level of interfering signals. With reference to "grasshopper noises," the idea, mentioned by Mr. Turner, of reducing the effective interference from the side-bands of a neighbouring station by cutting down the amplitude of the interfering signals at the detector stage and restoring the attenuated side-bands of the wanted signals by audio-frequency distortion, is very important. One must, however, bear in mind that if the higher frequencies are removed before the detector stage, when they are restored the ground noise at the detector will be accentuated. I should be interested to hear of any practical experience of this effect. If development is to proceed along the lines of this idea we shall have to consider all possible means of accentuating the upper frequencies after the detector stage, and this may prove to be an important consideration in loud-speaker design. It was interesting to hear Mr. Turner state that in comparing two systems with different cut-off frequencies it was necessary to present the two alternatives in quick succession, in order that the difference might be appreciated. This would indicate that the gain in quality of reproduction was but a slight compensation for the resultant loss of selectivity, and on this account manufacturers would be reluctant to increase the frequency range of their receivers. In my opinion we are not yet using to the best advantage the limited frequency range imposed by the present state of the ether.

Dr. W. F. Rawlinson: Problems connected with the selectivity of broadcast receivers become ever more important as the number of high-power broadcasting stations increases. Comparisons of receivers and discussion of their characteristics would be greatly facilitated if some definition of selectivity could be agreed upon. Prof. Fortescue's two figures of merit do not appear, however, to cover the whole of the problem; in fact his figure (*a*) giving the area of the response curve as compared with the ideal appears to have no definite meaning. Assuming the receiver under consideration to give a somewhat peaked curve; at what point does he propose to make the height of the ideal curve equal to that of the actual curve? This point, which will obviously decide the relative areas, can be varied at will. A better way of aiming at such a figure of merit would be to construct an ideal curve of rectangular form having as base a frequency range of 50 to 10 000 cycles per sec., and an area equal to that of the actual curve of the receiver between the limits of zero and 20 000 cycles per sec. (Anything above the latter frequency would be inaudible.) Counting the actual area of the receiver curve which lies within the ideal curve as positive, all areas of the receiver curve which lie outside as negative, and any area of the ideal curve not filled by the actual curve as negative; the ratio of the algebraic sum of these areas to the area of the ideal curve would be the figure of merit for the response curve as a whole. Prof. Fortescue's proposals will only give the low-frequency response curve of the receiver, and this has little to do with the selectivity. For instance, a receiver with no high-frequency circuit at all, but having a simple detector resistance coupled to the aerial and a band-pass low-frequency filter with a sharp cut-off at 50 and 10 000 cycles per sec., would give perfect results according to Prof. Fortescue's two figures of merit; yet it would be hopelessly unselective. The measurement of the sound-intensity output for a given high-frequency input may give a figure of merit applicable to the case of ordinary-type receivers used in or near London, but it is not of so much value for receivers to be used at a distance from a high-power local station. From aural observation on the South Coast it appears that the signals from Mühlacker are often 10 to 100 times as strong as those from London Regional, and at such times it is the shape

of the high-frequency resonance curve outside the ideal band which is all-important. Unless the attenuation at 9 kilocycles per sec. from the carrier frequency is greater than 100 we shall receive the carrier and one side-band of the unwanted station, and these will be received at greater strength than the programme of the wanted station, and no audio-frequency correction will get rid of the interference. The figures of merit proposed by Prof. Fortescue would not show up this defect, even with the modifications suggested. A receiver which cut down to 30 per cent at 5 000 cycles per sec. would apparently be considered satisfactory on the basis of the proposed figures of merit, yet it might prove very unselective under the conditions of reception suggested above. True selectivity must be associated with the high-frequency part of the receiver, to which any figures of merit must apply. The following is a possible way of defining two figures of merit. Plot the high-frequency resonance curve of the receiver for a continuous-wave input of constant amplitude at various frequencies. Measure the actual area within a band of $\pm$ 4 500 cycles per sec. of the frequency to which the receiver is tuned. Construct a rectangle of the same area on the base of $\pm$ 4 500 cycles per sec. about the mean frequency. The first figure of merit (*a*) depends on the maximum departure of the actual curve from the mean height, i.e. the height of the rectangle. If this is not greater than 50 per cent it will not be noticeable in the audio-frequency output. The second figure of merit (*b*) expresses the ratio of the height of the rectangle to the height of the actual resonance curve at 9 000 cycles per sec. from the mean frequency. For receivers used near London a figure (*b*) of about 10 might be good enough, but for receivers used on the South Coast this figure should be of the order of 1 000. Experience shows that moderate quality free from interference is preferable to ideal quality and another station breaking through. Since in practice the carrier waves of stations are only 9 kilocycles per sec. apart, one cannot hope to avoid interference and cross modulation if one retains frequencies much above 5 000 cycles per sec. in the transmitter output. Whilst I do not think that the loud-speaker really affects the selectivity, I cannot support the suggestion that modern types of loud-speakers have a cut-off at 2 000 cycles per sec. Modern loud-speakers are much better than Prof. Fortescue would have us believe. The questions of shock and interference due to atmospherics and tramway systems, etc., must clearly be considered in connection with selectivity problems. In obtaining high-frequency selectivity we must guard against circuits capable of maintaining free oscillations for a considerable period of time.

Mr. D. N. Corfield: The discussion of the problem of frequency range seems to centre round the question of whether in order to eliminate interference it is desirable to have a range of only 4 to 5 000 cycles per sec. and put up with poor speech. Such a frequency range will give exceedingly good "commercial" speech, but it will not give lifelike speech; a frequency range of about 8 000 cycles per sec. is necessary if the sibilants are to be reproduced properly. Such a range renders necessary some form of band-pass tuning, but this introduces difficulties because the side-bands of the interfering station will come into the band width at their full strength. On the other hand, we may use instead some form of circuit giving high selectivity, and then correct for the side-band cutting in the audio-frequency stages. Such an arrangement produces a different effect, because with a selective circuit very little interference is produced by a station whose side-band frequency is receivable but whose carrier frequency is not. The accepted explanation of this is that if there is a carrier spacing of 10 kilocycles per sec. and the receiver cuts off at 8 000 cycles per sec., a 6-kilocycle interfering signal is demodulated as 4 000 cycles per sec.; in other words, the interfering side-band becomes inverted. It is well known that the highest frequencies contain the least power, and the result is that when these become demodulated they are automatically reduced in strength, since they are inverted. If we are going to get a sufficient number of stations into the allotted wavelength range, the single-side-band system will have to be adopted, either at the transmitter or at the receiver. If it is adopted at the transmitter, all the receiving sets in use at present will have to be replaced by new ones. Alternatively, we could arrange to receive only one side-band of a double-side-band transmission by employing a quartz-crystal resonance circuit, which gives a very sharp response characteristic and can be arranged to cut off either side-band at will. This system would enable one to receive a transmission even when there was an interfering transmission working on a frequency only a few hundred cycles per sec. above or below that of the wanted station. Unfortunately this applies only to one side: if there are two interfering stations, one of slightly higher and the other of slightly lower frequency than that of the wanted station, single-side-band reception will not eliminate interference. A further difficulty which presents itself in connection with the commercial use of a band-pass tuning circuit is that variation of the wavelength tuning causes a variation in band width, and nothing short of a very complicated filter will remove this defect. If a very selective circuit is employed it is found that the shape of the resonance curve remains almost identical over the whole wavelength range, and one would therefore require about the same degree of low-frequency correction throughout. It seems to me that a low-frequency correction circuit is much more likely to remain stable when installed in a private house than is a high-frequency band-pass circuit.

Mr. F. Murphy: Prof. Fortescue emphasized the necessity for a definition of selectivity: in my opinion such a definition must depend upon the conditions to be met, as clearly if there were only one broadcasting station in the world there would be no selectivity problem. In the area where I live the field strength from Brookman's Park is about 300 mV per metre, and that from Mühlacker is 1·5 mV per metre, so that if I desire to receive signals from the latter station my receiver must have a selectivity sufficient to discriminate against the adjacent channel of a station 200 times as strong. There are three forms of interference, namely ordinary heterodyne interference, intelligible modulation interference, and side-band interference. It occurred to me to investigate whether any one form of resonance circuit would give greater freedom from interference

than any other, assuming that a certain audio-frequency response had to be obtained. Assume that one station is transmitting with a modulation depth M_1; the strength of the side-band is $\frac{1}{2}M_1$, and the response in the receiving circuit is $\frac{1}{2}M_1\theta$. Assume that the second station has a carrier strength of x units and modulation depth M_2, so that the strength of its side-band is $\frac{1}{2}M_2x$ and the response in the receiving circuit is $\frac{1}{2}M_2x\theta$. If we divide one response by the other, θ cancels out, and the ratio of the interfering side-band to the wanted side-band is M_2x/M_1. In other words, it is quite independent of the shape of the resonance curve if the same audio-frequency response is obtained. The only way of getting rid of the side-band interference is to make $\theta = 0$. I recently had occasion to investigate a system which uses a very low-decrement circuit, and I was told that in this particular system the important feature was the free vibrations set up by the applied signal. If a modulated sine wave of e.m.f. is applied to a simple resonant circuit, the resultant can be expressed by two sets of terms. One term represents the free vibration of the circuit and the others the forced vibrations. The coefficient of the free vibration term depends only on the accidental value of the applied e.m.f. at zero time of application to the circuit. This free-vibration term cannot, therefore, be a measure of the modulation. We are dependent on the other terms in exactly the same way as we are in the case of the more normally damped circuits in common use. Returning to the question of the definition of selectivity, I think this should involve three terms. The first term should define the selectivity in terms of the field strength which it would discriminate against in the adjacent channel. The second term should be a statement of the percentage audio-frequency response at, say, 4 kilocycles per sec. off tune. The third term should define the volume-level at which the tests are conducted.

Mr. H. A. Brooke: I should like to refer to the necessity for discriminating between definitions of selectivity which apply to one side of the detector stage, and those which apply to the other. The difficulty with regard to neighbouring transmissions which are capable of giving interference cannot be overcome merely by limiting the audio-frequency response, owing to the fact that cross modulation will occur in the detector itself. Selectivity must therefore be defined on the high-frequency rather than on the audio-frequency side. If interference is to be eliminated under the present conditions of a total separation of about 9 kilocycles per sec., the highest audio frequency that it is permissible to transmit and receive must necessarily be limited to about 4 500; otherwise there is always trouble due to the neighbouring side-bands.

Mr. H. L. Kirke: I recently investigated the problem of stray side-bands and the cut-off at 5 000 cycles per sec. by carrying out a test on two transmitters of frequencies separated by 9 kilocycles per sec. One was supposed to be giving the transmission which was required, and the other the interfering transmission. In the interfering-transmitter circuits I inserted an arrangement enabling me to switch in and out a filter circuit cutting off at 5 000 cycles per sec. The receiving circuits were so arranged that no programme interference was audible, but there was strong side-band interference. I found that frequencies above 5 000 in the neighbouring transmission created no interference in the receiver. Mr. Harvey Fletcher has recently published* in America curves giving the average energy to be expected in speech and music over the frequency range, and these curves show that although the human ear appreciates frequencies above 5 000 the intensities at which these frequencies are normally transmitted by musical instruments or the human voice are very low indeed. There is therefore no argument in favour of cutting off in the transmitter at 5 000 cycles per sec.; it is better to leave the higher frequencies for those people who are fortunate enough to be able to appreciate them. As regards Mr. Willans's reference to the frequency characteristics of microphones, I should like to state that the microphone we normally use has a rising frequency characteristic both above and below 1 000 cycles per sec., rising up to about 6 decibels at 4 000 to 6 000 cycles per sec. and cutting off fairly sharply above 6 000 cycles per sec. All our amplifiers have straight-line characteristics to within a decibel or so, and we are therefore sending out an excess of the audio frequencies of the order 4 000–5 000 cycles per sec. The response of an untreated condenser microphone is liable to be 15 decibels higher at 4 000 or 5 000 than it is at 1 000 cycles per sec., when one is speaking in a direct line with the microphone; in other directions the response will be lower. We have recently been experimenting in two of our studios with a new type of condenser microphone which we believe will respond to frequencies well above 10 000 cycles per sec. It has a sensibly flat frequency characteristic. Tests in our studios show that everybody can distinguish the presence of the higher audible frequencies in the output from loud-speakers of modern design. The majority of people prefer to have these frequencies present and they like the flat response given by the microphones, whatever may be the frequency characteristic of the loud-speaker. When listening with a receiver which has a cut-off before the detector of 6 decibels at 5 000 cycles per sec. and 14 at 8 000 I can tell at once whether the new type of condenser microphone is being employed. With regard to the question of stray side-bands, we have made many tests on the question of the difference between general interference and side-band interference, all of which tend to show that the shape of the frequency characteristic is the important factor. In an arrangement whereby total demodulation could be made to take place either by complete removal of the interfering carrier or by demodulation in the detector, provided our receiver had otherwise flat frequency characteristics we should expect to experience considerable side-band interference. Our tests show that this interference actually occurs. By using a circuit with a radio-frequency characteristic which can remove all frequencies above 5 000 cycles per sec. on each side of the wanted carrier, we can eliminate side-band interference. If, instead, we place immediately after the first detector a low-pass filter which cuts off at 5 000 cycles per sec., the same result will be produced. Consider the case where we obtain complete demodulation due to the use of a linear detector, the field-strength ratio of the two carriers being 10 or 12 to 1. If the difference between the carrier frequencies is 9 kilocycles

* *Bell System Technical Journal*, 1931, vol. 10, p. 849.

per sec., we have in the anode circuit of the detector a 9-kilocycle note which has the same modulation as the interfering station. The system is like the intermediate-frequency circuits of a super-heterodyne receiver. If we remove all the frequencies associated with the interference we shall experience no interference at all. If, on the other hand, we do not remove all these frequencies the interference will be audible as side-band and not as programme interference. If these currents or voltages encounter any subsequent non-linear device in the apparatus, such as a valve or a transformer, they will again be rectified as in the second detector of a super-heterodyne circuit, and whole-programme interference will be experienced. Thus one can get rid of side-band interference by cutting off after the detector. With regard to cut-off at high audio frequencies, several years ago we carried out tests with what were then considered to be the best types of loud-speakers, and we found that most people were agreed that an overall cut-off at 5 000 cycles per sec. was tolerable. They liked the higher frequencies to be included if possible, however. Very few people could notice when frequencies above 7 000 were cut off. Turning to the question of the use of highly-selective simple tuned circuits and tone compensation, I am impressed by the importance of amplitude distortion in and before the detector valve. If we use a non-linear detector we shall certainly produce distortion, resulting in the appearance of harmonics which were absent originally. The process of amplifying the higher frequencies to a greater extent than the low, exaggerates all these distortion terms. If any of the side-bands are wrongly phased or have the wrong amplitude in relation to one another, we shall also experience distortion. As an example of this, we recently tested a set made up on the principle of a super-heterodyne circuit with very sharply tuned intermediate-frequency circuits and compensation for the frequency characteristic in the low-frequency circuits. When observing frequency characteristics we noticed that an applied modulating frequency of 200 cycles per sec. produced in the loud-speaker a note whose frequency was estimated to be about 800 cycles per sec. The analysis of the output was as follows:—Fundamental frequency 1·6 per cent; 2nd harmonic 30 per cent; 3rd harmonic 9 per cent; 4th harmonic 37 per cent; etc., up to the 10th harmonic. We then proceeded to observe the high-frequency characteristics by injecting a variable-frequency carrier into the receiver and measuring the resultant rectified current. The high-frequency characteristics were found to be very asymmetrical, due to various so-called band-pass filters which had been incorporated to reduce the signal strength of the second channel, and presumably also to errors in the tuning of the intermediate-frequency circuits. The shape of the overall characteristic is important. I prefer a tail-off to a cut-off at 5 000 cycles per sec. In the design of receivers manufacturers are up against the problem of endeavouring to make a receiver which is acceptable to all sections of the public. In the first place, as Mr. Murphy suggested, some people want to receive a signal strength of $1\frac{1}{2}$ millivolts per metre when the interfering signal of an adjacent channel has a strength of 300 millivolts per metre. To do this, one must be prepared to accept a cut-off at 4 000 or 5 000 cycles per sec. in the overall characteristic. Secondly, there are those who are receiving 25, 50, and 100 millivolts per metre, and who are quite content to go on listening to their local programme. For them the problem is easy. Thirdly, there is the question of designing a type of set suitable for the people who live in areas where the signal strength is 5 or 10 millivolts per metre, and it is here that the problem of knowing where to cut off is most difficult.

Mr. H. Dewhurst: I have been asked to show a few slides of a filter (referred to by Mr. Barton) which was

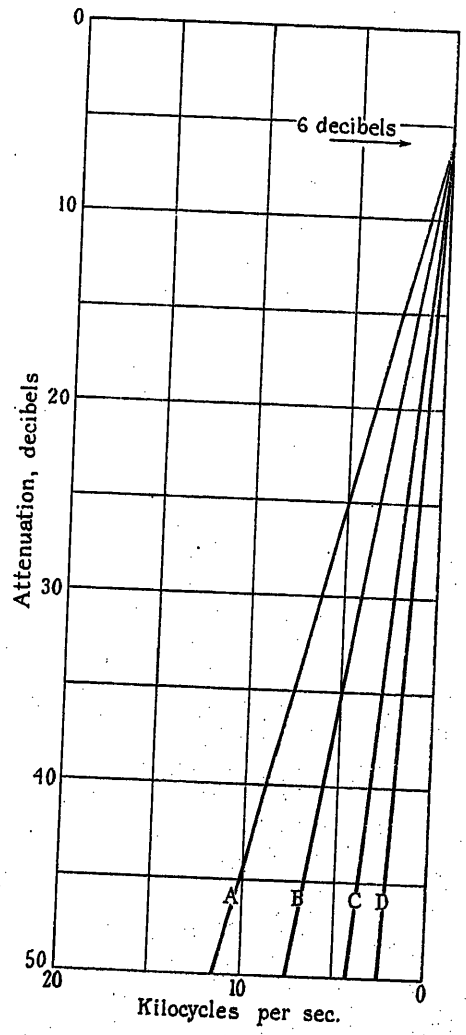


FIG. A.—Average filter slopes, reduced to 300 kilocycles per sec.

A.—180 kilocycles per sec.; slope 2·7 decibels per kilocycle.
B.—300 " " " ; slope 4·5 " " "
C.—500 " " " (R.A.E.) } slope 8·0 " " "
C.—300 " " " (R.A.E.) } slope 8·0 " " "
D.—300 " " " ; slope 13·5 decibels per kilocycle.

A, B, C, are commercial 3-element intermediate-frequency filters. D is a 4-element intermediate-frequency filter designed by the Royal Aircraft Establishment.

constructed at the Royal Aircraft Establishment, Farnborough, for use in a super-heterodyne receiver. The filter design was based on the telephone practice

developed by Zobel and Campbell in America. The first consideration in designing a filter is that of the impedance out of, or into, which it is to work. If the filter is worked at an impedance level for which it is not intended, reflection losses occur. For example, if a band-pass filter with a flat-top characteristic were used under wrong impedance conditions the flat top would degenerate into two peaks and the sides of the filter characteristic would become less steep. The only existing high-frequency filters which we knew about were of the 3-element type incorporating a tuned circuit in either the series or the shunt arm, and a condenser in the other; the usual arrangement being a coupling condenser in the series arm. Filters of this type are being used on commercial short-wave telephony and telegraphy. They are cheap to construct and are fairly easily tuned and handled. Fig. A shows the characteristic curves of various 3-element filters. Our first attempt (Filter C), also a 3-element filter, was an improvement on the existing types. A drawback of the 3-element filter, however, is that the losses in the coils modify the performance; instead of a flat top, a rounded top is obtained to the characteristic. A first essential, therefore, is to have very good coils. A further drawback is that this type gives an attenuation of a high

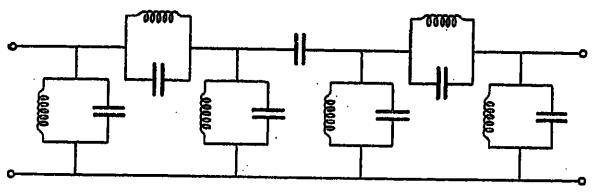


FIG. B.—Circuit of Royal Aircraft Establishment intermediate-frequency filter (D), composed of two complementary 4-element, double-M derived, π sections, and one 3-element π section.

order where it is not required. We therefore tried what is known as the " infinity cut-off " type of filter. This gives a cusp which pulls down the slope to a higher degree than would an increase in the magnification of the constituent coils. Our second design (Filter D) gives an attenuation of 34 decibels $2\frac{1}{2}$ kilocycles per sec. away from the point where the flat top starts. Thus, D would attenuate by 34 decibels an interfering signal $2\frac{1}{2}$ kilocycles per sec. away, whereas C would attenuate it by only 20 decibels. Filter D is of the 4-element type with a 2-element (see Fig. B) circuit tuned in both series and parallel arms. The series members provide the infinity cut-offs. The coils used in this filter are placed in copper cans to maintain their frequency characteristics constant and prevent interaction. Used in this way they still have a magnification of 200. The amplifier is provided with a semi-aperiodic tuned-anode coupling coil; and there are three contacts which automatically connect up the filter as soon as this is dropped into position.

Mr. C. E. G. Bailey: Experiments with a highly selective receiver incorporating audio-frequency correction show that this arrangement has certain advantages. If in order to correct the high-frequency cut-off we put in a resonance circuit to obtain the last iota of correction, the audio- and radio-frequency responses alike will drop after the selected upper frequency limit, and the consequent overall cut-off will be very steep. Accordingly, these circuits can eliminate that type of interference where the side-bands of the two transmissions do not overlap. Interference of the type where the side-bands do overlap can only be eliminated with the help of the demodulation effect. As has been pointed out, 2 carriers, each with a pair of side-bands, produce in the detector 27 components, some assisting and others tending to neutralize each other. The demodulation effect consists in the counteracting of certain components present in the output of the detector. It is clear that if a receiver with a sharp response curve is capable of receiving single-side-band telephony, it is also capable of responding to the note produced by the carrier or one of the side-bands of an interfering wave. How does such a receiver discriminate between these two? As Mr. Turner pointed out, in the first case there is only one side-band, whereas in the second there are two. It is easy to see that if we injected single side-band telephony signals into such a receiver we should get some sort of response: but the solution is to be found, I think, in the fact that we still get the carrier and, to a certain extent, the remoter side-band of the unwanted station, and demodulation balances out certain audio-frequency components produced by the two unwanted side-bands. This can be confirmed experimentally by the fact that if to a selective circuit one adds additional circuits, thus making a band-pass system which cuts off very rapidly, interference may increase. This may account for the selectivity of receivers of the quartz-crystal type, which, apart from the tremendous increase in response near the resonant frequency, behave as rather poor single-circuit receivers. I know of no way of eliminating that type of interference where both sets of side-bands overlap both carrier waves. Mr. Willans mentioned the effects of noise in connection with corrected receivers. One of the startling characteristics of this system is the decrease in the noise background. I account for this effect in the following way. If we imagine the noise spectrum to consist of a number of components spaced at unit intervals, the noise-level is produced partly by the interference of the carrier with each component and partly by the interference of the components among themselves. A perfectly level amplifier would give a noise response due to the latter cause proportional to $N!$, but in the case of a sharply-tuned amplifier there is little cross-heterodyning between the noise components, so that this source of noise disappears. Selective receivers employing resonant audio-frequency circuits for correction suffer from phase distortion at the upper frequencies, and, in the limit, resonance of long duration may occur round about the 4 000-cycle region. This type of distortion condemns resonated audio-frequency correctors as a method of obtaining quality with selectivity. Finally, we need a definition of selectivity. Since demonstration effects are complicated it is advisable to base this on the simplest considerations, and I suggest that selectivity should be defined in terms of the degree of mistuning in kilocycles per sec. which is required to reduce the signal level of a wave by 40 decibels. In order to avoid the logical confusion of using a term which is greater when the number describing it is less, I propose to name this

quantity the " connivance " of the receiver and not the "selectivity."

Mr. G. Builder: A question relating to receiver design which has been very little discussed is the distortion of transient modulation in tuned circuits of low decrement. In this connection some interesting effects may occur in band-pass filters having a double-peak resonance characteristic. The effect of the double peak is to superimpose a damped low-frequency oscillation on the original transient modulation; this oscillation may be regarded as a surging of energy between the coupled circuits of the band-pass filter. The dependence of the superimposed frequency on the separation of the resonance peaks may be readily confirmed by experiment. The effect may also be considered to be due to the combination of two transients set up at the resonant frequencies, and it may equally well be interpreted in terms of side-bands. I should like to point out that in the case of sinusoidal modulation, if one employs a band-pass circuit in which the ratio between the gain at the side-band frequencies to that at the carrier, multiplied by the modulation ratio, is greater than unity, serious distortion (chiefly second-harmonic) is introduced into the modulation. I have given these particular examples, not because they are directly relevant to the subject of selectivity, but in order to show that we must consider the possibilities of distortion of the transient modulation when designing circuits of low decrement.

Mr. T. Wadsworth: While there is little doubt that a certain degree of selectivity must be allowed, the real criterion of a receiver from the user's point of view should be the quality of the output which it delivers. From what has been said by the previous speakers it seems to me that there are two schools of thought regarding this question of selectivity and quality. The first school regards the quality of the receiver as its essential characteristic, and Mr. Ashbridge's remarks have shown that the B.B.C. belongs to this school. The second school regards the receiver as an extremely selective device, and considers that the quality which can be achieved at present is good enough for broadcast reception. We are of opinion that the first school is right. It follows as a corollary that we must regard the present frequency separation, 9 kilocycles per sec., as inadequate, because with this separation one can only get 4 500 cycles per sec. of audio-frequency range. The second school favours ultra-selective circuits and the use of tone control. It is questionable whether this method is fundamentally correct, because there is no evidence that by the use of tone control one can reinstate something which has already been taken away in order to provide increased selectivity. In connection with the B.B.C. transmissions, it would be an advantage to know the frequency characteristics of all the stations. Contrary to Mr. Turner's opinion, we have recently recorded on a film frequencies up to 7 000 or 8 000, and have found these films, both on speech and on music, to be of better quality than the average broadcast reception. We have also made a loud-speaker which has a response at 9 000 cycles per sec. and have found by experiment that the presence of this high frequency in the reproduction is beneficial, particularly in connection with speech.

Mr. W. J. Brown (*communicated*): It has been adequately demonstrated that the upper limit of the audio-frequency response of a sensitive receiver is approximately half the kilocycle spacing of adjacent broadcasting stations. With the present 9-kilocycle separation of stations the highest audio-frequency permissible is therefore 4 500 cycles per sec. It is not to be expected that any real improvement will be obtained by merely extending the station spacing to 11 or 12 kilocycles per sec. (with a corresponding maximum audio frequency of 5 500 or 6 000 cycles per sec.), since the increase in range would be much less than an octave in the musical scale. To produce any real effect at least a full octave should be added, which involves one of two alternatives, either (*a*) increasing the broadcast station spacing to 18 kilocycles per sec., which involves halving the number of stations; or (*b*) enforcing the suppression of one side-band from every broadcasting station, leaving the carrier and a single side-band to be transmitted. Transmission of a single side-band only has been rightly condemned, as it necessitates a special homodyne receiver; but a carrier and single side-band can, of course, be received on any normal receiving apparatus. Such a transmission would have the additional advantage of reducing the harmonic distortion in reception. When two side-bands and a carrier are received, even the best of detectors cannot avoid the introduction of a double-frequency component due to the beating of the two side-bands with each other. The elimination of one side-band from the transmission would eliminate this double-frequency component.

Prof. C. L. Fortescue (*in reply*): The outstanding feature of this discussion is the unanimity of opinion in favour of an extension of the audio-frequency range amongst those speakers who have had the opportunity of carrying out careful comparisons. Mr. Ashbridge and Mr. Kirke, Mr. Turner and Mr. Wadsworth, Mr. Corfield and others, all advocate extension up to 8 000 or even 10 000 cycles per sec. One or two speakers advocate a limitation to 5 000 cycles per sec., but apparently only on the grounds of unavoidable compromise. The feasibility of this extension of range with the present separation of carrier waves by 9 000 cycles per sec. has not been fully debated. Mr. Turner, Mr. Barton, Mr. Cohen and others envisage very complicated receivers; Mr. Corfield and Mr. Brown advocate single-side-band working in spite of the difficulties mentioned by Mr. Ashbridge and in my opening remarks. Mr. Bailey appears to favour very highly selective circuits combined with tone correction, but other speakers express doubts with respect to this system. Several speakers, and particularly Mr. Scroggie, point out the remarkable results already obtained with the small separation of carrier waves now used, the explanation being, no doubt, that given by Mr. Kirke and others, viz. that the energy in the high-frequency audio components is small. The advantage to be gained by linear detectors has been mentioned by Mr. Turner, Mr. Kirke and Mr. Bailey, but without making the matter very clear. That a strong carrier on an adjacent wavelength but not giving audible beats will almost blot out an incoming programme is certain; but when this carrier is modulated and when side-bands of both transmissions beat audibly with both

carriers the situation is quite different and far more complicated. The analysis is laborious but favours the view that in this case there is no immunity from interference to be obtained by a straight-line rectifier. The final conclusion appears to be that the greater perfection of rendering resulting from an extension of the audio-frequency range can only be obtained by increasing the separation of carriers. Actual experience must, of course, be the final arbiter, and it is unfortunate that so few people have actually heard the results obtainable by extension up to a frequency of 8 000.

An important question of design has been raised by Dr. Rawlinson in claiming that true selectivity must reside in the high-frequency stages of the receiver. It is obvious, of course, that if both the carrier and a side-band of an interfering programme are received on the high-frequency side, no selectivity on the audio-frequency side can have any effect. Provided, however, that the carrier of the interfering programme is eliminated in the high-frequency stages, it certainly becomes possible to eliminate very high beat notes either in the audio-frequency stage or even in the acoustical conversion in the loud-speaker. The essential point is that the beating of interfering side-bands shall not produce an audible note within the desired range of audibility.

One of the most important points raised in my opening remarks is the ability of the non-technical general public to handle a very selective receiver. Mr. Turner has alluded to the difficulties experienced, but several other speakers advocating complicated receivers seem to have omitted this aspect entirely. The situation has changed enormously in this respect during the last few years on account of the introduction of "ganging" of the controls. Provided that this ganging is sufficiently accurate, the public can probably be trusted to make a delicate adjustment with the accuracy necessary to give a good result. It is only necessary to watch an entirely non-technical person adjusting a receiver having ganged tuning and reaction control to realize the skill that is acquired in the course of a very brief experience. But in spite of this it seems very doubtful whether a receiver having more than two delicate adjustments would meet with public approval.

Finally there is the point raised by Mr. Willans of the non-linearity of the B.B.C. transmissions and the effects which this must have on the shape to be given to response curve of the ideal receiver. The present over-accentuation of the frequencies between 4 000 and 6 000 is almost certainly valuable with most of the more commonly used receivers, owing to the falling-off of their curves in this range. If this falling-off were not common there would probably be a great outcry against the action of the B.B.C. and an urgent demand for linear transmission characteristics!

DEVELOPMENTS IN THE TESTING OF RADIO RECEIVERS.

By H. A. THOMAS, M.Sc., Associate Member.

[From the National Physical Laboratory.]

(*Paper first received 5th January, and in final form 8th February, and read before the* WIRELESS SECTION *2nd March*, 1932.)

SUMMARY.

The paper describes the improvements in the technique of radio-receiver testing that have been made at the National Physical Laboratory. The arrangements now used for this purpose having been described in detail in Part 1, a proposed specification of methods of testing broadcast receivers is given in Part 2, together with experimental results obtained on such receivers. This specification is examined as to its applicability to the relative comparison of widely different types of receivers, and a classification is suggested so as to diminish the number of tests which it is necessary to make in order to assign a figure of merit to a particular receiver.

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Part 1. DEVELOPMENTS IN TECHNIQUE.

(1) INTRODUCTION.

The apparatus installed at the National Physical Laboratory for testing the performance of radio receivers has been modernized and partially rebuilt, and while it still conforms to the general arrangement described in a previous paper,* considerable modifications have been made. This part of the paper gives an account of these modifications and a general description of the apparatus.

The original apparatus involved difficulties in the method of obtaining and measuring the modulated signal e.m.f. for application to the receiver under test. These difficulties have now been eliminated. Originally no accurate means were provided for giving very small radio-frequency variations on either side of a particular known value, such as are required to obtain selectivity characteristics. Provision has now been made for this, together with an improvement in the frequency stability of the system.

In any routine tests on receivers, rapidity in making the tests is important, and consequently ease of operation has throughout been regarded as a primary requirement. The attenuating system has been improved and made suitable for tests at very high frequencies. The range of input voltage which can be obtained has been greatly increased, also the screening, both of the feed system to the attenuating apparatus and of the attenuator itself.

The present arrangement is schematically illustrated in Fig. 1. Cabin B, which was described in the previous paper,* consists essentially of a completely shielded

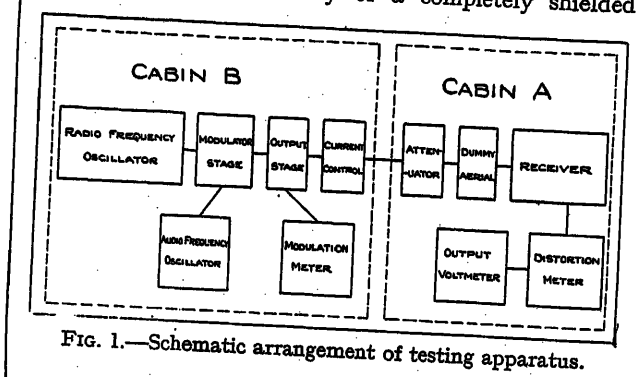


FIG. 1.—Schematic arrangement of testing apparatus.

room with a mercury trap-door seal. The generating apparatus which is enclosed by this screened room has been reconstructed, and consists of the master radio-frequency oscillator, a modulator stage supplied by a beat-tone audio-frequency oscillator, an output stage, a modulation meter, and a special device called a "current control." The radio-frequency oscillator has a range of from 10 to 50 000 kilocycles per second, and gives a good sine wave-form in the output stage. The audio-frequency beat-tone oscillator has a frequency range of from 20 to 10 000 cycles per second, the output containing less than 1 per cent of harmonics, and the modulator stage is capable of giving a correct modulation envelope up to a depth of modulation of 100 per cent.

The value of the current in the attenuator is controlled by the operator in cabin A by means of the current control device, which varies the output current but preserves a constant resistance load on the output stage of the generating system. Cabin A, which was also de-

* H. A. THOMAS: "A Method of Measuring the Overall Performance of Radio Receivers," *Journal I.E.E.*, 1930, vol. 68, p. 475.

* *Loc. cit.*

scribed in the previous paper, has remained substantially the same, except that improved screening has been constructed to minimize stray fields set up by the attenuator. The attenuator itself has been considerably altered to give greater range, and it is now more completely screened. A series of dummy aerials has been constructed for use with different classes of receivers, and these dummies represent the constants of the various types of aerials that would be used with receivers of different frequency ranges.

The audio-frequency output power is measured electrostatically in terms of the voltage across known resistances in the output stage of the receiver. The purity of the output is also examined by a harmonic distortion meter, which expresses the R.M.S. value of the whole of the harmonics as a percentage of the R.M.S. value of the distorted wave.

(2) Design of Modulated Radio-Frequency Generator.

The production of a modulated radio-frequency current in the attenuator system by means which do not involve several separately-tuned circuits is difficult. The simplest method of obtaining a modulated output is to insert an audio-frequency voltage in series with the anode voltage supply of a simple oscillator. This method, however, gives rise to a pure audio-frequency component superimposed upon the modulated radio-frequency component of current due to the inter-electrode capacitance between the anode and grid of the oscillator valve. Such a component, even if it were only of the order of 1 per cent of the R.M.S. value of the modulated wave, would give rise to serious errors not only in the measurement of the current fed to the attenuator but also in the determination of the modulation percentage by the use of a double rectifier system (as explained later). Although this difficulty can be eliminated by loosely coupling a tuned circuit to the main oscillation circuit, this involves two separate tuned circuits—a slight operational drawback.

The most serious objection to this simple method of modulation is that it introduces frequency modulation as well as amplitude modulation, due to the fact that the generated frequency of a triode oscillator is dependent upon the anode voltage supply. Admittedly this is only a second-order effect, but the frequency change so introduced may be many kilocycles per second, which is a serious matter when testing a very selective receiver. Consequently, to eliminate these difficulties a simple master radio-frequency oscillator, very lightly loaded and giving a small output, is used, the output from this oscillator being taken to the modulator stage. This modulator consists of a radio-frequency amplifier stage with tuned-anode circuit, and it is so biased that the characteristic working point lies on the non-linear part of the I_a/V_g characteristic It is possible, by suitable adjustment of the magnitude of the radio-frequency input e.m.f. and the value of the bias voltage, to obtain a linear relationship between the radio-frequency current in the tuned-anode circuit and the voltage supply to the anode. Once this condition has been arrived at by experiment, it is found to hold at all frequencies. When this condition obtains, a modulating e.m.f. inserted at an audio frequency into the anode circuit of the modulator gives rise to a modulated output in the anode circuit free from frequency distortion, since the amplitude of oscillation of the radio-frequency master oscillator remains sensibly unchanged, except for very minute changes introduced into the input impedance of the modulator stage by the varying anode potential. The two tuned circuits are ganged, and a fine adjustment or "trimming condenser" is provided to establish resonance. The output from this modulator stage is taken to a large-power output stage with an aperiodic load circuit, which delivers about 150 milliwatts to the current control circuit.

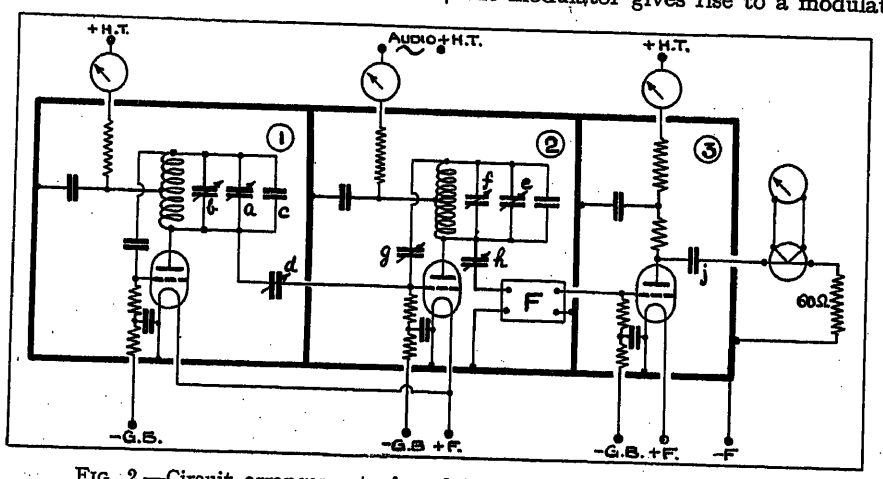


Fig. 2.—Circuit arrangement of modulated radio-frequency generator.

The general circuit arrangement of the modulated radio-frequency generator is shown in Fig. 2. The small-power master oscillator (1) is provided with a small variable condenser "a" of 15 $\mu\mu$F for giving small changes in frequency (a few kilocycles per second) for selectivity determinations. The main tuning condenser "b" is shunted by a fixed condenser "c," which ensures that the value of the capacitance is always large, this condition giving a good wave-form. The output from this oscillator is passed to the modulator

stage (2) by means of the coupling condenser "d," the value of which is definitely fixed after the condition for a linear relation between output and anode voltage of the modulator has been established by trial.

The main tuning condenser "e" of this stage is ganged to the main tuning condenser of the radio-frequency oscillator, and a trimming condenser "f" is provided. The audio-frequency voltage derived from the beat-tone oscillator is inserted in series with the anode voltage supply to this stage. Neutrodyning is found to be necessary, since without it the unbalanced inter-electrode capacitance between the anode and grid gives a radio-frequency output to the modulator when there is no anode voltage. This neutrodyne condenser is shown at "g."

The modulated radio-frequency energy is taken to the output stage (3) by means of the coupling condenser "h," which acts as a volume control. The audio-frequency component in the anode circuit is filtered out by means of the high-pass filter F.

The output valve supplies the line to the current control and attenuating system, and the d.c. component of the anode voltage is eliminated by the condenser "j." The impedance of the output line (60 ohms) is constant for all arrangements of the attenuator. The current output is measured by means of the thermo-junction shown. This junction serves only to give an approximate idea of the output to the operator in cabin B; the actual measurement of the current to the attenuator is made in cabin A.

The three stages of the modulated radio-frequency generator are carefully screened from each other, and the whole unit is enclosed in a heavily-screened metal box. A number of coils are plugged into the oscillator and modulator stages to cover the large frequency band required, and no difficulty is experienced in obtaining satisfactory operation over the range required.

(3) Measurement of Modulation Percentage.

Owing to the selective properties of the tuned-anode circuit in the modulator stage, the value for the modulation depth of the output radio-frequency current supplied to the attenuating system is not the same as that calculated in the modulator by means of a measurement of the peak audio-frequency voltage and the known linear law relating the output to the anode voltage of the modulator. At very low audio frequencies, the simple law holds, and it can be used as a means of checking any meter used for the purpose of measuring the modulation percentage of the current in the output circuit. This is due to the fact that the side-band cut-off is negligible at very low audio frequencies. It is safest, therefore, to measure the modulation percentage of the current in the output circuit; a separate modulation meter, the input to which is taken from the outgoing line circuit, has been constructed for this purpose.

The direct observation of modulation percentage is a rectification problem. The rectification of a modulated wave gives rise to a current having a direct and an alternating component, these being related to each other in a manner depending on the characteristic of the rectifier and the modulation percentage. The design of a modulation meter therefore resolves itself into the design of a rectifier of calculable behaviour, with means of measuring separately the direct and the alternating components of the output. The simplest calculable rectifiers are those operating by square-law or linear rectification. K. W. Jarvis* has described a modulation meter based on square-law rectification and consisting essentially of two anode rectification valve-voltmeters, one recording the direct and the other the alternating component of the rectified current. The instrument used in the present investigation has been developed on similar lines, and the theory on which it is based is given in full in the Appendix.

The calibration so obtained was compared with an experimental calibration obtained at a low audio frequency by using the simple modulation law which holds in the modulator stage and assuming no side-band cut-off in the anode circuit of this stage. Satisfactory agreement was obtained between the two calibrations. The calibration of the second rectifier is independent of frequency up to 5 kilocycles per second, and from 5 to 10 kilocycles per second the error is only of the order of 1 per cent. The values of the components used in the filter circuit connecting the two rectifiers are so chosen as to prevent any radio-frequency energy from giving a readable deflection on the second rectifier.

(4) Complete Generating Equipment.

The complete assemblage of the generating apparatus is shown in Fig. 3. The various components already described are mounted in panel form on a rigid metal frame. The modulated radio-frequency oscillator (1) occupies the top portion of the panel, and the three condenser controls operate the tuning, trimming, and volume-control condensers. Milliammeters are inserted in the anode supply to the master oscillator and the power output stage, the former to indicate the oscillating condition and the latter to show the presence of overloading.

The modulation meter (5) is situated below the oscillator, and the two microammeters (10) used with this instrument are placed on the shelf in front of the panel. The beat-tone audio-frequency oscillator (2) supplies a variable-ratio transformer (3) which in turn supplies the modulator through screened leads. The control of the output from this oscillator is at (4), and by means of the switches (6) the audio-frequency oscillator can be connected either directly to the attenuator system for calibrating audio-frequency amplifiers or to the terminals (11), which can be connected to telephones for checking frequency or for testing loud-speakers. The output current is indicated by the thermo-junction (7) and its associated microammeter (9). A small coil (8) may be inserted in series with the output line for coupling to a wavemeter for calibration purposes. The milliammeter (12) in series with the anode supply to the modulator is used to adjust the trimming condenser to the resonance condition. A voltmeter panel and switch (13) is provided to measure all battery voltages: this is necessary in order that faults may be rapidly located.

*K. W. Jarvis: "Radio Receiver Testing Equipment," *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 664.

(5) Attenuating System.

The general arrangement of the means provided for obtaining known radio-frequency voltages for application to the dummy aerial system is shown schematically in Fig. 4. The leads from the generating equipment in cabin B are taken to the current divider, which consists of the series and shunt resistances R_1 and R_2 respectively. These resistances are arranged in the form of two parallel circles of studs, and the two contact arms are connected together mechanically. The values of the resistance steps per stud on R_1 and R_2 are so arranged that the division ratio I_2/I_1 is proportional to the number of studs (100 in all). At the same time the resistance load of the whole system—including the screened resistance in cabin A—is constant at a value of 60 ohms. By this means, control of the current divider from cabin A gives a 1 per cent change of current per stud and at the same time maintains a constant load on the output stage of the oscillator, thereby preventing any second-order frequency variations due to the alteration of the input impedance of this stage on the modulator. The divided current I_2 is passed through a special screened resistance R of the type described in a previous paper.* The voltage across this resistance may be used to supply the dummy aerial.

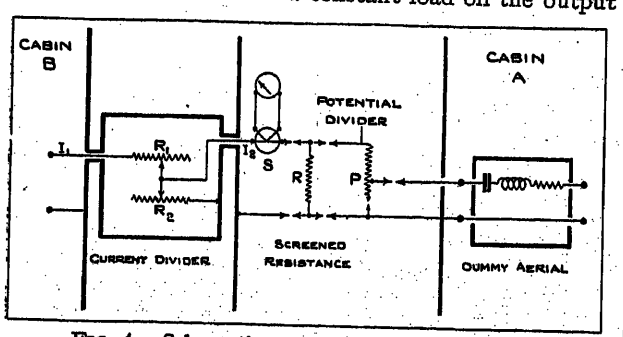


Fig. 4.—Schematic arrangement of attenuator.

* *Loc. cit.*

Since the possible current range as measured at S is about 10 : 1 and the range of resistances is about 40 : 1, the total voltage range is about 400 : 1 and the minimum measurable voltage is about 1 millivolt. To increase this range, a series of resistance potential dividers P are connected across the screened resistance R, and these can reduce the voltage to 1/1 000 of the value across the screened resistance. The use of this divider, which has an output resistance of about 1 ohm, enables a radio-frequency voltage range of from 1 microvolt to 1 volt to be applied to the dummy aerial system. Great care has been taken in the construction of these potential dividers to ensure that there is no frequency error up to 30 000 kilocycles per second, and at frequencies above this the error due to the inductance of the wires used in the divider is calculable.

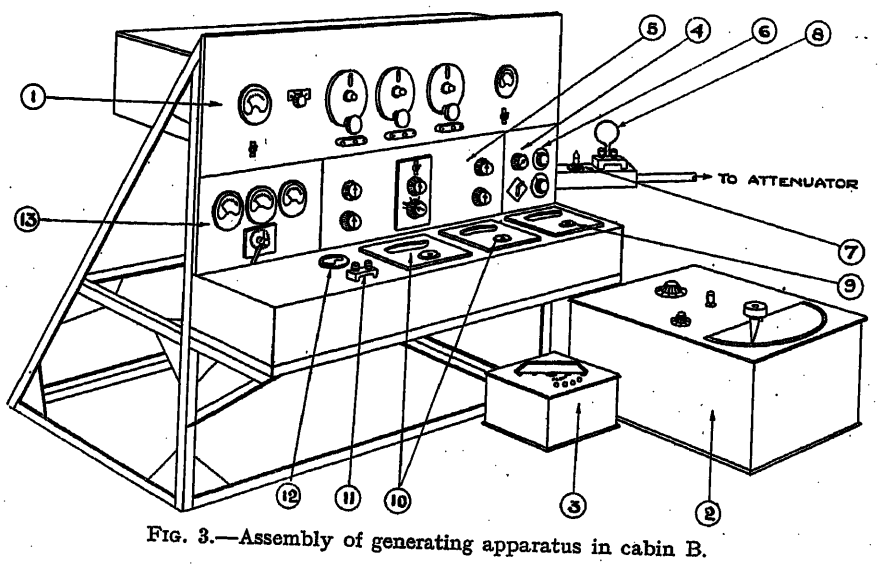


Fig. 3.—Assembly of generating apparatus in cabin B.

The arrangement of the attenuator is shown in detail in Fig. 5. The concentric lead from the current divider is taken to the screened box containing the thermo-junction for current measurement, and thence to a bayonet socket B into which one of the screened resistances is plugged. The potential leads from this resistance terminate in contacts C which engage with two insulated pins connected to two of the three contacts D. The series of potential dividers are mounted on the periphery of a disc, rotation of which brings any one of

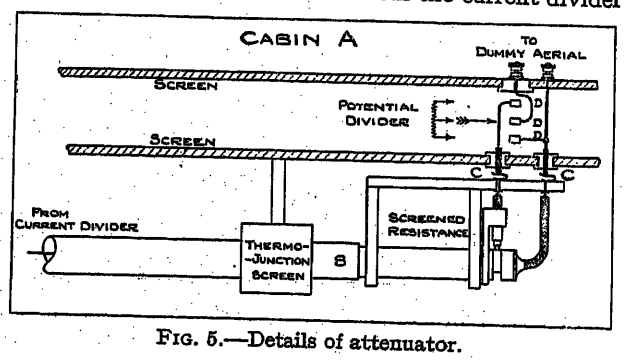


Fig. 5.—Details of attenuator.

them into engagement with the contacts D. The tapping contact and the earthed side of the screened resistance are taken to the terminals connected to the dummy aerial. Metal screens isolate the divider from both the screened resistance and the dummy aerial, and by the use of this screening system all direct induction effects are eliminated. The values of the effective resistance of the attenuator for its various combinations have been measured by a d.c. potentiometer, contact effects being eliminated by taking the mean value of the resistance so obtained with reversal of current.

The known e.m.f. is applied to a dummy aerial having constants equal to those of an aerial suitable for use with the receiver under test. The dummy aerial is made up as a small screened unit, and for broadcast receivers the following values recommended by the Institute of Radio Engineers* have been selected: capacitance 200 $\mu\mu$F; inductance 20 μH; resistance 25 ohms. These values are considered to be typical of an aerial having an effective height of 4 m. The equivalent e.m.f. to be applied to the dummy aerial by the attenuator to reproduce the condition required for the use of this standard aerial is 4 times that of the field strength in volts per metre. The potential applied to the receiver is calculated from the known resistance of the attenuator and the R.M.S. value of the current supplied, measured by the thermo-junction.

The R.M.S. value of a modulated wave having the form

$$E_{max.}(1 + m \sin nt) \sin \omega t$$

is

$$(E_{max.}/\sqrt{2})\sqrt{(1 + \tfrac{1}{2}m^2)}$$

where m is the modulation depth.

TABLE 1.

Modulation percentage	Ratio $\frac{\text{R.M.S. value of modulated wave}}{\text{R.M.S. value of carrier only}}$
0	1
10	1·0025
20	1·010
30	1·022
40	1·040
50	1·061
60	1·087
70	1·116
80	1·148
90	1·185
100	1·225

In actual broadcasting the carrier wave of R.M.S. value $E_{max.}/\sqrt{2}$ remains constant, and hence with varying modulation depths the R.M.S. value of the modulated wave will vary if the carrier wave is to remain the same throughout. A correcting term must therefore be adopted for different modulation depths, and the input must be expressed in terms of the R.M.S. value of the carrier wave only. The value of the function $\sqrt{(1 + \frac{1}{2}m^2)}$ for various values of m is given in Table 1.

Hence, if the modulation percentage is increased from zero to 100 per cent, the R.M.S. value of the modulated wave will increase by 22·5 per cent and the input to the receiver must be increased by this amount to maintain the same carrier-wave amplitude. This correction is negligible for the standard conditions of 30 per cent modulation when we are applying a signal e.m.f. to obtain a specified output in a sensitivity test, but it becomes important when a test of amplitude distortion is being made, i.e. when we are examining the proportionality of the output with respect to the modulation percentage at a constant input e.m.f.

(6) Measurement of Output.

The output load used throughout a test on a receiver may be the actual loud-speaker or telephones with which the receiver is normally used, but since receivers are supplied for use with any type of loud-speaker it is more usual to use as an output load a specified non-inductive resistance. This method is not ideal, for, as the author has shown,* the electrical characteristics of the loud-speaker affect the amplification of the receiver, owing to the fact that the input impedance of the power-valve stage depends upon the nature of the load in the anode circuit. Fortunately, however, the effect is small, and since it would be impossible to adhere to a particular loud-speaker for each receiver, the method of using a non-inductive load is permissible as a means of obtaining a general performance test of the electrical properties of the receiver itself. The value of the optimum resistance load to be used with any particular output valve is specified by the manufacturers, who use this value in giving the maximum undistorted power output. Since tests have shown that the magnitude of this resistance is not critical, the value suggested by the manufacturers has been adopted.

The output is measured in terms of the voltage across this resistance, which readily gives the power output; this is usually adjusted until it equals the maximum undistorted value the valve is rated to give. A double-range electrostatic voltmeter is used for the measurement of the output voltage, this method having been found to be more reliable than valve-voltmeter methods and quicker and more sensitive than a current measurement. The output is given in terms of R.M.S. values.

The output is also passed through a distortion meter, which gives the percentage of harmonics present in the output circuit. The meter is essentially an audio-frequency bridge which can be balanced at the fundamental frequency, leaving the harmonic remainder unbalanced and capable of measurement. The bridge, which has been developed by F. M. Colebrook on the lines suggested by I. Wolff,† is arranged as shown in Fig. 6. The meter is inserted in series with the output current circuit, i.e. the terminals X,Y, are connected in series with the output load. An e.m.f. equal to IR_1 or IR_2 is thus applied to the points A, B, of the bridge according as the switches are placed in position 1 or position 2. With both switches on 1 (the switches in

* "Proposed Standard Tests on Broadcast Radio Receivers," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 1282.

* H. A. Thomas: "Effect of Output Load upon Frequency Distortion in Resistance Amplifiers," *Experimental Wireless*, 1931, vol. 8, p. 11.

† I. Wolff: "The Alternating Current Bridge as a Harmonic Analyser," *Journal of the Optical Society of America*, 1927, vol. 15, p. 163.

practice being interlocked), the bridge is closed and an e.m.f. IR_1 is applied to it, I being the R.M.S. value of the current in the output circuit. The resonant arm CB is now tuned to the standard modulation frequency of 400 cycles per second used for these tests, and the resistance R_3 is adjusted to give balance for the fundamental. The system now becomes a simple resistance bridge. This balance is detected by means of the amplifier and telephones connected to the transformer T. The harmonics are now left unbalanced. Since the impedance of the resonant arm CB is large compared with that of the remaining three arms at all harmonic frequencies, and since the impedance of the transformer T is also large at all frequencies, the voltage across T due to the harmonics is to a close degree of approximation given by

$$IR_1 \frac{R_4}{R_4 + R_5}$$

The amplifier has an adjustable control for varying its amplification, and this control is now set to give a measurable output as read on the thermo-junction and galvanometer J. The switches are thrown over to

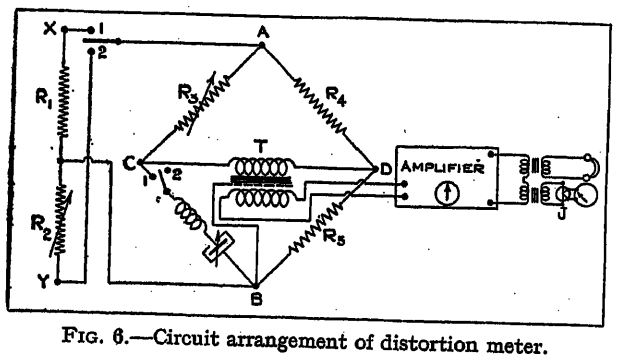


FIG. 6.—Circuit arrangement of distortion meter.

position 2, and the e.m.f. now applied to the points A, B, is IR_2. The bridge is now open, consequently the voltage applied to the transformer is

$$IR_2 \frac{R_4}{R_4 + R_5}$$

Leaving the amplifier adjustment unchanged, the value of R_2 is adjusted to give the same output in J.

The ratio of the R.M.S. value of all the harmonics taken together to the R.M.S. value of the distorted wave (including the harmonics and fundamental) is therefore given by R_2/R_1, and the measurement becomes dependent on the ratio of these two resistances only.

The variable resistance R_2 consists of two ribbons of constantan resistance wire about $\frac{1}{8}$ in. wide wrapped in grooves on the edge of a circular disc of keramot, forming a non-inductive bifilar circuit. The disc rotates, and contact with it is made by two stationary flat brushes composed of constantan wires. This type of brush has been found to give very satisfactory behaviour from the point of view of constancy of calibration. A second calibration made after an interval of several months was found to be identical with the first within the degree of accuracy with which the setting could be determined. The value of this variable resistance (R_2) is about 1·5 ohms, and the values of the fixed resistance R_1 may be 2·9, 6·6, or 12·16 ohms, depending on the range of harmonic content required to be measured. The meter is capable of measuring harmonic contents from just under 1 per cent to 50 per cent. The resistances R_4 and R_5 have values of 50 and 100 ohms respectively; an electric screen is inserted between the two windings of the transformer to eliminate capacity-current effects, and the whole bridge is screened by being enclosed in an earthed metal box.

From the above description it will be seen that the apparatus is capable of measuring a modulated radio-frequency voltage of from 1 microvolt to 1 volt at any frequency within the range 10 to 50 000 kilocycles per second. The accuracy of the voltage measurement is chiefly dependent upon that of the current measurement, and in the absence of any simple alternative method a non-contact thermo-junction is used at present. Within the limits imposed by the use of this instrument the accuracy is of the order of 1 per cent, which is quite adequate for radio-receiver testing.

The modulation frequency may have any value from 20 to 10 000 cycles per second, the exact figure being set by beating with a standard tuning-fork, while the accuracy of the measurement of modulation depth is within 2 per cent over the whole range from 0 to 100 per cent.

Part 2.—Proposed Method of Specifying Performance of Broadcast Receivers.

(1) Introduction.

In this part of the paper an attempt will be made to draw up a schedule of tests by means of which the relative performance of different broadcast receivers may be assessed. No apology is needed for making such an attempt, and although certain details of the proposals put forward may be subject to criticism on technical grounds, it is believed that there is a definite need for such a specification in order that the public may have information as to the quality of the apparatus which they use.

The difficulties of drawing up a satisfactory series of tests are many, due first of all to the several properties of the receiver which have to be considered and to the varying importance of different qualities depending on the purpose and method of use, and secondly to the fact that receivers have several controls, any one of which may produce large changes in the performance of the apparatus. It is owing to this fact that the testing of broadcast receivers is much more difficult than the testing of the majority of other electrical appliances where the conditions of operation are narrowly limited.

Hitherto, it has been the practice of manufacturers and testing laboratories to express the performance of a receiver by a number of graphical results. It is found to be extremely difficult to use such results for any direct comparison of the relative merits of different receivers, however, owing to the varying nature of the experimental conditions and to the impossibility of determining the performance under a set of conditions differing from those used in the particular test.

These facts point to the need for some standard of test methods and performance, so that both manufac-

turers and purchasers of receiving apparatus may have a simple means of assessing the merits of particular receivers. The essential properties of a receiver may be classified as (*a*) sensitivity, (*b*) selectivity, and (*c*) audio-frequency response and purity factor. To group these three together and give an overall performance figure may appear to be a dangerous procedure, but an attempt has been made to do so, and whatever may be the disadvantages of such a course it cannot be denied that an overall figure of merit is of great value in so far as it introduces a comparative method of assessing performance. The difficulty of so doing arises from the fact that the test specification must be such as to assess fairly the properties of the whole receiver and also give due weight to each individual property. In making this attempt, therefore, the author is fully aware that any proposed specification is open to detailed criticism; but if the result of such criticism leads to a standard specification he will consider himself amply rewarded.

(2) Sensitivity and Classification of Receivers.

Measurements on radio receivers have hitherto included sensitivity tests, in which the output was plotted against the input over the working range of radio-frequencies for different settings of the volume and retroaction controls. Since it is possible with modern receivers to obtain a very large sensitivity range by adjustments of this kind, such tests do not reveal any vital characteristics of the receiver, except in the case of super-sensitive receivers used for telegraphy where other considerations are made subservient to sensitivity. In these cases, however, the background noise has to be measured, and the ratio of wanted to unwanted signal determines the operational limit to the sensitivity.

It will usually be found that when the sensitivity is high the other properties of the receiver—particularly the audio-frequency characteristics—are adversely affected. Hence it is preferable to fix the sensitivity at some rated value and obtain the other properties of the receiver when operating under these standard input conditions.

Most broadcast receivers are required to operate under certain known local conditions; for example, the field strength is known if the receiver is to work in a broadcast service area, and the amount of interference due to other radio stations, mains hum, tramways, etc., is approximately known from experience and the topographical conditions. Hence a receiver should be tested to examine the extent to which it will give true reproduction of telephony under the known conditions of working.

In a general scheme of specifying the performance of the many different types of receivers, it is felt that it would be better to substitute for the sensitivity test a type classification, and to determine the properties of the receiver within the limits so imposed. This method possesses the advantage of eliminating a mass of irrelevant tests.

P. P. Eckersley* has suggested the following field strengths as suitable for the various service areas from a broadcasting station:—

(1) "A" service area, in which the field strength is greater than 10 millivolts per metre.
(2) "B" service area, in which the field strength is greater than 5 millivolts per metre and less than 10 millivolts per metre.
(3) "C" service area, in which the field strength is greater than 2·5 millivolts per metre and less than 5 millivolts per metre.

It is suggested that a fourth "D" class area should be recognized for field strengths below 2·5 millivolts per metre.

Any receiver submitted for test should be classified as suitable for one or more of the service areas defined above, and the test signal applied to it would correspond to the minimum field strength of that area. In the case of a "D" class receiver, it is suggested that the signal applied should correspond to a field strength of 1 millivolt per metre. It is probable that a receiver may be suitable for more than one service area, in which case separate tests should be made at the inputs corresponding to the various field strengths. The input would in all cases be applied to the receiver through the standard dummy aerial system described on page 118.

The output from the receiver presents another difficulty, in so far as the possible outputs from different receivers vary so widely. It is suggested, therefore, that the output power should be classified in a similar manner according to the type of output circuit adopted. The following scheme for broadcast receivers is proposed:—

(1) Very small output—below 250 milliwatts.
(2) Small output—250 to 500 mW.
(3) Medium output—500 to 1 000 mW.
(4) Large output—1 000 to 5 000 mW.
(5) Very large output—above 5 000 mW.

The output of the receiver would be measured in the optimum anode-circuit load resistance specified by the valve manufacturer as suitable for the valve used. The output resistance would in all cases be adjusted to this optimum value and the receiver would be tested with the maximum rated output.

The normal output level would in practice be very much less than this maximum, but since the receiver must be capable of handling the maximum output on transient high modulation percentages, it is better to test it at the maximum rated output.

According to this proposed specification, therefore, a "B 3" receiver is one that will give a medium output of 500 to 1 000 milliwatts when a field strength of 5 millivolts per metre is applied to the standard aerial. In such a case, a fixed input of 20 millivolts would be applied to the dummy aerial, since its effective height is taken as 4 m, and the receiver would be adjusted to give the maximum rated output with a modulation frequency and percentage of 400 and 30 respectively. This receiver adjustment would remain constant for all further tests at that particular radio frequency. The procedure would be repeated for any other test frequency. The number of frequencies at which tests are

* P. P. Eckersley: "The Design and Distribution of Wireless Broadcasting Stations for a National Service," *Journal I.E.E.*, 1928, vol. 66, p. 501.

made should be sufficient to establish by interpolation the general performance at intermediate frequencies. For the high-sensitivity receivers of class "D," the appropriate field strength adopted for the test would be stated.

(3) Selectivity.

The method of test proposed by the Committee on Standardization of the Institute of Radio Engineers* consists in plotting the input required over a band of frequencies covering resonance to give a constant output in the power stage with a constant modulation frequency and percentage of 400 and 30 respectively. This test is not altogether satisfactory, since it does not simulate the actual conditions of operation. It is better to maintain a constant radio-frequency input e.m.f. and to plot the output power when the input frequency is varied over a narrow band on either side of resonance. Such a test, however, gives the result in graphical form and the necessary deductions must be made from the graphs so obtained.

In seeking some test procedure which will give a figure for selectivity by which different receivers may

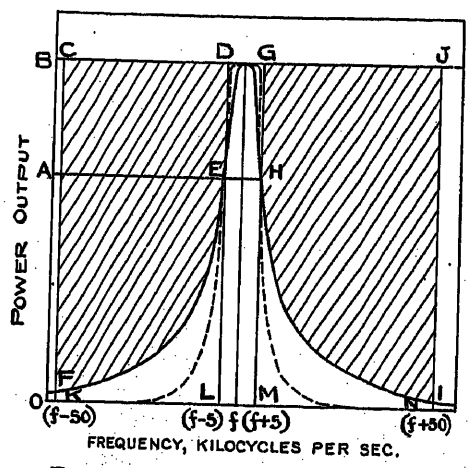


Fig. 7.—Definition of selectivity.

be compared, it is soon realized that simple ratios of the output at resonance to the output at frequencies differing from that of resonance by known small amounts do not give sufficient information and, in fact, may lead to quite misleading results. For example, suppose the resonance curve of a receiver is found experimentally to be as shown in Fig. 7 by the heavy-line curve, in which the power output is plotted against the radio frequency using linear scales for constant input e.m.f. One suggested method of expressing selectivity is to give the ratio of the response at a frequency displaced a known amount from resonance, to the response at the resonance frequency. In view of the crowded nature of the frequency allocations of broadcasting stations, it is considered that the upper audio-frequency limit which should be catered for is 5 kilocycles per second, and hence a receiver giving no side-band cut-off should have a uniform response over a total band width of 10 kilocycles (i.e. 5 kilocycles on either side of resonance). Referring to Fig. 7, it can be seen that the ratio OA/OB is the same for the simple tuned circuit as for the band-pass filter-circuit characteristic given by the dotted-line curve, yet the two circuits are obviously quite different so far as selectivity is concerned.

It is clear that from the point of view of radio-frequency selectivity the form of the response characteristic within the limiting frequencies $(f - 5)$ and $(f + 5)$, where f is the resonant frequency in kilocycles per second, is not what we wish to measure, since the form of this portion of the curve will determine the audio-frequency response and will make itself manifest in the later tests on this characteristic. The selectivity may be defined as a function of that portion of the response characteristic which lies outside the 10-kilocycle band, and it is suggested that the selectivity be expressed by the effective area of this curve between the 5-kilocycle line and another line separated from resonance by some arbitrary frequency. If 50 kilocycles per second be taken as this arbitrary frequency limit, we can express the selectivity as

$$\frac{1}{90P_f}\left\{90P_f - \left[\int_{f-50}^{f-5} Pdf + \int_{f+5}^{f+50} Pdf\right]\right\}$$

where f = resonant frequency in kilocycles per second,
P = power at any frequency,
and P_f = power at the resonant frequency.

This is represented graphically in Fig. 7 by the sum of the shaded areas CDEF and GHIJ divided by the sum of the rectangles CKLD and GMNJ. For a receiver having a perfect filter system which passed only those frequencies lying between $(f - 5)$ and $(f + 5)$ kilocycles per second, the value of this expression would obviously be unity; for any other characteristic the selectivity would be less than unity. This simple definition gives a figure which, although not so instructive as the plotted characteristic, forms a useful criterion of selectivity in most practical cases. It is suggested that this figure—expressed as a percentage—should be obtained at certain selected values of the resonant frequency, and that by its use different receivers could be compared at those frequencies. It is admitted that such a numerical statement of the selectivity does not give all the information contained in the actual response characteristic, but it must be remembered that the object of the specification is to obtain some simple figure which will act as a useful guide in comparing different receivers. With this object in view the suggested method of expressing the selectivity appears to be satisfactory.

Selectivity tests should be made at a very low modulation frequency of about 50 cycles per sec., so that the characteristic is virtually that which would be obtained with no modulation.

(4) Audio-Frequency Response and Purity Factor.

There are two important audio-frequency properties of a receiver:—

(*a*) The audio-frequency output power plotted against

* "Proposed Standard Tests on Broadcast Radio Receivers," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 1282.

the modulation frequency for constant radio-frequency input e.m.f. and constant modulation percentage,

(*b*) The harmonic distortion produced at various values of the output power up to the maximum rated output of the power stage.

(*a*) is important since it reveals the general response obtainable over the audio-frequency range.

Let us assume that the response characteristic is plotted on a logarithmic audio-frequency scale from 50 to 5 000 cycles per second and a linear power-output scale, as shown in Fig. 8. Here again, we seek some means of assigning a numerical value to this characteristic which will express its relative merit with respect to the desired uniform response over the stated range. The simplest method, that of giving the ratio of the maximum to the minimum power output, is unsatisfactory, since it permits widely different divergent characteristics to have the same value of this ratio. To express the characteristic as the area of the curve

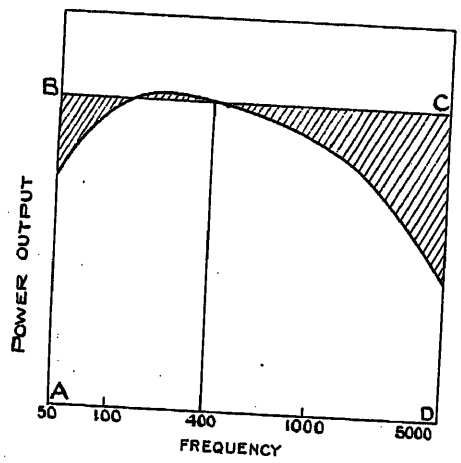


FIG. 8.—Definition of audio-frequency response.

between the frequency limits of 50 and 5 000 cycles per second divided by the rectangle having the same base and a height equal to the maximum ordinate, is also unsatisfactory and for the same reason.

A better method is to express the characteristic as the ratio of the sum of the shaded areas (see Fig. 8) to the area of the rectangle ABCD, where AB is the value of the power output at the standard frequency of 400 cycles per second. This method gives a figure which is more nearly a function of the departure from the mean value. Since we desire a perfect characteristic to have a numerical value of unity, we must define this audio-frequency response figure as

$$1 - K\left(\frac{\text{Sum of shaded areas}}{\text{Area of rectangle ABCD}}\right)$$

where K is some arbitrary constant which we must choose so as to grade various characteristics in proportion to their degree of excellence. Since, according to this definition, a characteristic which decreased according to a linear law from some value at 50 cycles per second to zero at 5 000 cycles per second would have a value of about 0·44 if K were equal to unity, and since we can say that such a characteristic would represent an exceedingly bad form of audio-frequency distortion, it is suggested that K be given the value 2, in which case such a bad characteristic would yield a numerical figure of 0·12, or 12 per cent. Hence the audio-frequency response can be defined as

$$1 - 2\left(\frac{\text{Sum of shaded areas}}{\text{Area of rectangle ABCD}}\right)$$

It will be found that this method gives a comparatively satisfactory method of discriminating between a good and a bad audio-frequency characteristic.

The usual form of the harmonic-content characteristic is as shown in Fig. 9, and a numerical value can be assigned to this characteristic by defining the purity factor as

$$1 - K\left(\frac{\text{Shaded area AEFD}}{\text{Rectangle ABCD}}\right)$$

where K is again some arbitrary constant.

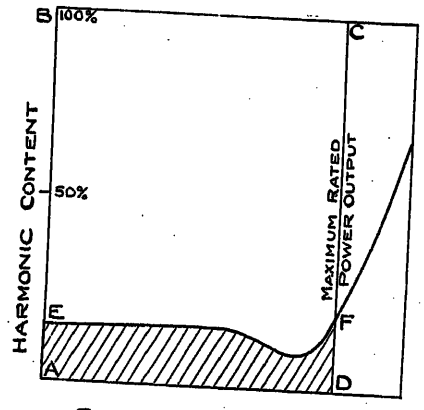


FIG. 9.—Definition of purity factor.

It is more difficult to assign a value to K, but since harmonic distortion probably plays a very important part in contributing to poor-quality reception, we desire to choose K in such a way that the effect of strong harmonics is to give a large reduction in this numerical figure. Tests have shown that a typical harmonic content for a fairly good receiver is 10 per cent. It is claimed that in first-quality receivers employing straight-line rectification and push-pull output circuits the harmonic percentage has been reduced to values below 2 per cent, and that a 5 per cent harmonic content is readily noticeable. In view of this, it is suggested that K be assigned the value 4, in which case we can define the purity factor as

$$1 - 4\left(\frac{\text{Shaded area AEFD}}{\text{Rectangle ABCD}}\right)$$

For an output containing no harmonics, the purity factor is 100 per cent.

(5) OVERALL PERFORMANCE.

In order to see what values the previous definitions will give when applied to a typical receiver, two cases

from actual tests are given. In the first case, a typical 3-valve receiver employing retroaction and using a grid-circuit rectifier, an audio-frequency amplifier stage,

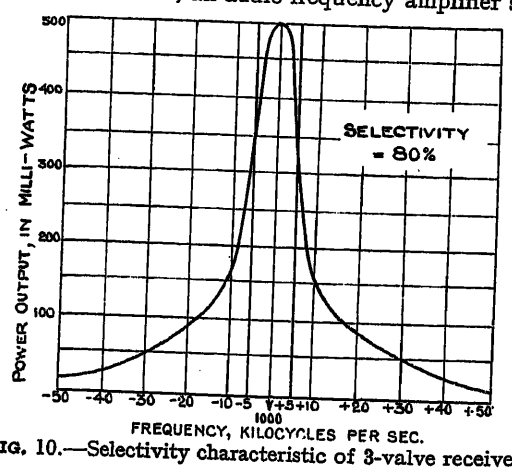


FIG. 10.—Selectivity characteristic of 3-valve receiver.

and an output stage, was tested. It was found to be suitable for a "B" service area, and consequently the input to the dummy aerial was adjusted to correspond

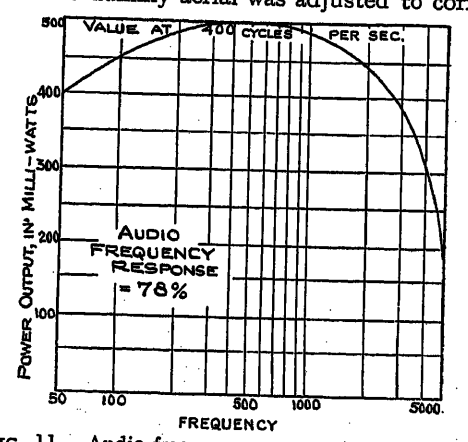


FIG. 11.—Audio-frequency response characteristic of 3-valve receiver.

to a field strength of 5 millivolts per metre. The radio frequency used for the tests was 1 000 kilocycles per second. The output stage was found to correspond to

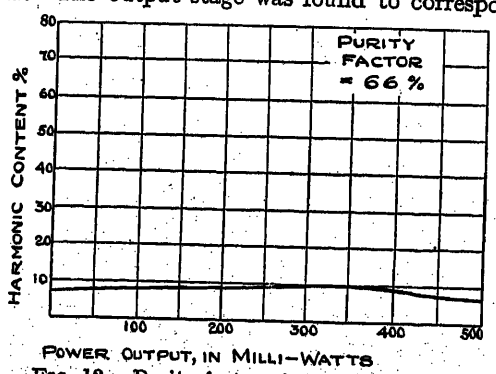


FIG. 12.—Purity factor of 3-valve receiver.

Class 2 (250–500 milliwatts), its maximum rated output being 500 milliwatts. This output was adopted throughout the tests.

The selectivity characteristic is shown in Fig. 10, from which it will be seen that there is an appreciable cut-off at 5 kilocycles per second departure from the resonant frequency. This is a very general type of selectivity curve for a receiver with a simple tuned circuit and retroaction, without band-pass tuning. Adopting the definition already given, the selectivity figure for this curve is 80 per cent.

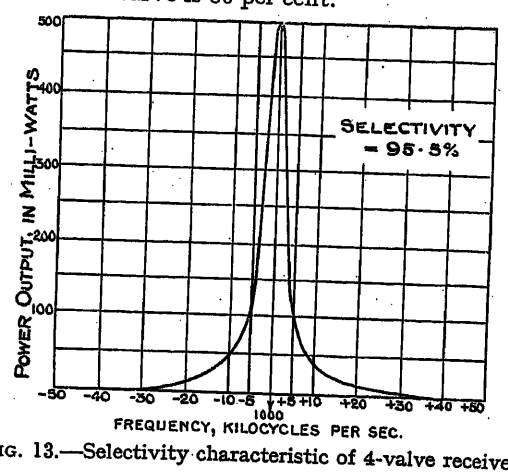


FIG. 13.—Selectivity characteristic of 4-valve receiver.

The audio-frequency response characteristic is shown in Fig. 11. The rapid drop in sensitivity at frequencies above 2 000 cycles per second is due to the shape of the response characteristic shown in Fig. 10, and the audio-frequency response for this curve is found to be 78 per cent.

Lastly, the purity factor (see Fig. 12) is found to be 66 per cent.

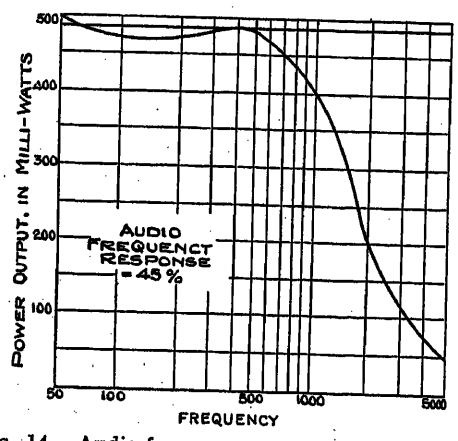


FIG. 14.—Audio-frequency response characteristic of 4-valve receiver.

A 4-valve receiver was examined in a similar manner. This receiver had a screen-grid stage, a grid-circuit rectifier, an audio-frequency amplifier, and a power-output stage similar to that of the previous 3-valve receiver. It was found to be suitable for a "C" service area, and is therefore a "C 2" receiver. The input was adjusted to correspond to a field strength of 2·5 millivolts per metre, and the selectivity characteristic was obtained. This characteristic, which is shown in Fig. 13, exhibits a greater side-band cut-off than that of the

previous receiver, and without retroaction it was found impossible to improve it. The selectivity of this receiver (95·5 per cent) is greater than that of the previous one, but the audio-frequency response characteristic (Fig. 14) shows how serious the side-band cut-off has become. The audio-frequency response figure obtained from this latter characteristic is 45 per cent, while the

TABLE 2.

Receiver	Class	Test frequency	Selectivity	Audio-frequency response	Purity factor	Overall performance figure
		kilocycles per sec.	per cent	per cent	per cent	per cent
3-valve	"B 2"	1 000	80	78	66	41·2
4-valve	"C 2"	1 000	95·5	45	58	24·9

purity factor—given in Fig. 15 as 58 per cent—is much the same as for the previous receiver. The results obtained on these two receivers are collected in Table 2.

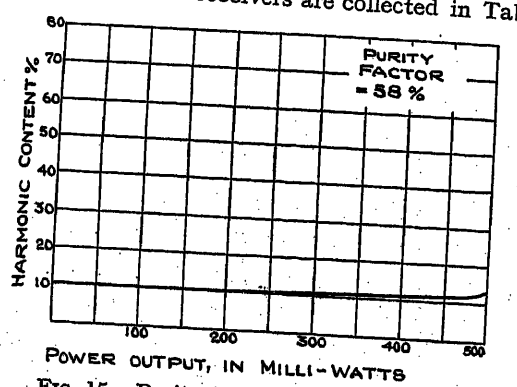


FIG. 15.—Purity factor of 4-valve receiver.

The overall performance figure is the product of the three separate characteristics expressed as a percentage.

If retroaction had been used in the 3-valve receiver so as to convert it to a "C 2" receiver, the side-band cut-off would have been far greater and the audio-frequency response figure correspondingly lower. It is clear, therefore, that this method of classification prevents high figures from being obtained by the excessive use of retroaction, and at the same time ensures that a poorly-selective receiver is not awarded a high figure of performance. The overall figure acts as a useful general guide to the performance, but it should only be given in conjunction with the three separate figures from which it is built up.

It may be argued that the test curves shown in Figs. 10 to 15 do not represent modern practice. While it is true that they do not represent a modern band-pass receiver with linear rectification, they are typical of many commercial receivers without band-pass tuning. As an example, Fig. 16 shows the audio-frequency response characteristic of a well-known modern commercial 3-valve "all-mains" receiver, and this demonstrates that the characteristics given are in keeping with general practice.

One advantage of the proposed method of specification is that it does not fix a definite minimum performance for each of the three properties. To obtain such a minimum figure it is necessary to make a large number of tests on various classes of receivers, and it is exceedingly difficult to say what minimum requirements are essential for satisfactory operation. The author feels that it would be better to adopt some such classification as the above, and then, as information was obtained for different receivers, certain values would be found by experience to be applicable to the limiting performance. As the general standard of design improved, these values would rise automatically and act as a strong stimulus to further improvement. Ultimately, a minimum value for each separate test, together with a minimum value for the overall figure, could be adopted as a satisfactory criterion of the efficient behaviour of a receiver.

In conclusion, the author wishes to express his indebtedness to Dr. R. L. Smith-Rose for his constant

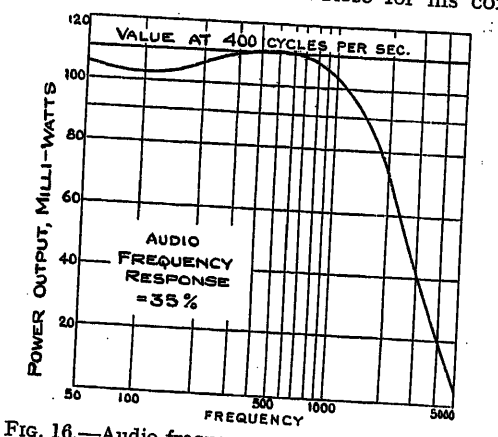


FIG. 16.—Audio-frequency response characteristic of a typical modern receiver.

interest and helpful suggestions, to Mr. F. M. Colebrook for designing the modulation meter and harmonic distortion meter, and to Mr. C. W. Spencer, who helped in the constructional and test work.

APPENDIX.

THEORY OF MODULATION METER.

$$I = aV + bV^2$$

where I = anode-current change in first rectifier,
V = grid-voltage change,

a and b are constants of the circuit.

Now, for a modulated wave,

$$V = E_{max.}(1 + m \sin nt) \sin \omega t$$

where $E_{max.}$ = maximum value of carrier-wave e.m.f.,
m = modulation depth,
$n = 2\pi \times$ (modulation frequency),
$\omega = 2\pi \times$ (radio frequency).

The d.c. component of the rectified current is given by

$$I_1 = \tfrac{1}{2}bE^2_{max.}(1 + \tfrac{1}{2}m)^2$$

since

$$v^2 = E^2_{max.}(1+2m\sin nt+\tfrac{1}{2}m^2-\tfrac{1}{2}m^2\cos 2nt)(\tfrac{1}{2}-\tfrac{1}{2}\cos 2\omega t)$$

The a.c. component of the rectified current is given by

$$I_2 = \tfrac{1}{2}bE^2_{max.}(2m\sin nt - \tfrac{1}{2}m^2\cos 2nt)$$

Therefore, the R.M.S. value of I_2 is given by

$$I_3 = \frac{bE^2_{max.}}{2\sqrt{2}}m\sqrt{\left(4+\frac{m^2}{4}\right)}$$

If the signal input is adjusted by means of the potentiometer of the modulation meter to give a definite known change (k) in anode current,

Then $$\tfrac{1}{2}bE^2_{max.}(1+\tfrac{1}{2}m^2) = k$$

and $$I_3 = \frac{k}{\sqrt{2}}\cdot\frac{2m}{1+\tfrac{1}{2}m^2}\sqrt{\left(1+\frac{m^2}{16}\right)}$$

The audio-frequency voltage supplied to the second rectifier is $V = R_1I_3$, where R_1 is the anode-circuit resistance in the first rectifier.

Thus $$V = \sqrt{2}(kR_1)\frac{m}{1+\tfrac{1}{2}m^2}\left(1+\frac{m^2}{32}\right)$$

The second rectifier is calibrated experimentally by supplying an audio-frequency potential to its grid circuit. It should obey a square law, so that $\theta = KV^2$, where θ is the deflection in microamperes, K is the experimentally-determined constant, and V is the R.M.S. value of the audio-frequency potential supplied. By measuring R_1 and assigning a value to K within the square-law operational range of the first rectifier, we can calculate values of V for various values of m, and then convert these calculated values of V into values of θ from the calibration of the second rectifier. In this way the deflection in microamperes can be plotted against the modulation percentage for any assigned value of the anode-current change in the first rectifier.

Discussion before the Wireless Section, 2nd March, 1932.

Mr. P. K. Turner: I shall deal first of all with Part 2 of the paper. The author's proposal (page 120) of awarding an overall figure of performance to broadcast receivers seems to me to be an impossible one. For example, although his overall performance figures show the 3-valve to be better than the 4-valve set, we have to face the fact that the question which of those sets is better for a particular user depends on what that user wants. In other words, it is impossible in principle to give any such overall figure. The class "D" receiver referred to on page 120 is designed for distant reception, i.e. field strengths below 2·5 millivolts per metre, and I suggest that the signal strength of 1 millivolt per metre which is applied is much too high. A receiver of that type should give its full output at 25 microvolts per metre. I do not agree with the statement (page 121): "In view of the crowded nature of the frequency allocations of broadcasting stations, it is considered that the upper audio-frequency limit which should be catered for is 5 kilocycles per second." A good deal of propaganda work is being carried out at present with a view to convincing the ordinary listener that he does not require a higher frequency limit than 5 000 cycles per sec., the maximum which can conveniently and cheaply be provided for sound films and gramophone records. In my opinion, however, a good frequency response characteristic up to 8 000 or 9 000 cycles per sec. is necessary and can be obtained, in spite of the state of the ether. While I support the author's idea of judging selectivity by the amount that one can cut out over a wide frequency band, as illustrated in Fig. 7, I think that the scales of this diagram should be modified in the way described below. I would also press for a wider frequency band in Fig. 8, as it is not fair to base the figure for the audio-frequency response of a first-class receiver on a range of 50 to 5 000 cycles per sec. Further, any local irregularity in the response curve of a loud-speaker in the neighbourhood of 400 cycles per sec. would have an altogether disproportionate effect on the result as obtained from the author's calculation. If a loud-speaker were tested in the way suggested, a 100 per cent resonance at 400 cycles per sec. would result in the reactangle ABCD being doubled and its efficiency figure halved. I therefore suggest that the output used for purposes of comparison should not be that at 400 cycles per sec. but should be that corresponding to the mean height of the curve: this would be independent of local irregularities. My second point in connection with Fig. 8 is that I think the units of the vertical scale should be decibels. For example, the audio-frequency response of the 4-valve receiver of Fig. 14 is reduced to one-tenth of the full value at 5 000 cycles per sec. If, however, between 2 000 and 5 000 cycles per sec. the response had dropped to one-hundredth of the full value, although the additional area would not have been greatly different from that shown the actual change in performance would have been very large. The use of a decibel scale would really make the area of the rectangle ABCD disappear from the problem altogether. It is a pity that all three of the receivers the results of which are shown should be so bad. With regard to Part 1 of the paper, I should be glad of further details of the valves used in the radio-frequency amplifier, and of the adjustments which are necessary in order to obtain a linear relationship. Instead of the small variable condenser to give small changes in frequency for selectivity determinations, it would perhaps be preferable to have part of the inductance in the form of a small variometer, because this would enable one to make a definite percentage change no matter what the main frequency setting happened to be. A modulation meter based on approximately linear rectification is much easier to handle than one based on approximately square-law rectification. I should be glad of further details of both the current divider and the potential divider, as I have found such instruments very difficult to make with any pretence to accuracy. They have to be extremely well screened, and usually screening upsets the calibration on account of

capacitance effects. Table 1 shows the corrections to be applied to the modulation percentage owing to the fact that the input was measured with an R.M.S. meter (thermo-junction), but I am surprised that this difficulty was not evaded by making the essential measurement with a valve-voltmeter, which reads mean volts and needs no correction if its calibration curve is linear. My own experience in less accurate work is that the convenience of the radio-frequency voltmeter outweighs in most cases the theoretical accuracy of the thermo-junction. With regard to the measurement of harmonics, it seems to me that a weak point in the author's method is that what is actually obtained is the sum of the R.M.S. values of all harmonics. Thus a receiver with an output of 10 per cent of second harmonic and nothing else would give exactly the same rating as another receiver with outputs of 5 per cent each of the second and third harmonics: yet it is curious that the one with the 10 per cent of second harmonic seems much more offensive to listen to. As far as I can judge, the effect of harmonics on the ear is more a function of the amplitude or percentage of the largest harmonic present —if it is of a low order (second or third)—than of the sum of all the harmonics. We therefore need an instrument which will measure the amplitude of the maximum harmonic rather than the sum of all the harmonics present.

Mr. F. S. Barton: I should like to know the size of cabin A, as it occurs to me that manufacturers and others may sometimes wish to submit other than broadcast receivers for testing. The author's dummy aerials—of which more details would be appreciated, especially for those not within the ordinary broadcast range—seem to me to be arranged specifically for the type of receiver that has aerial and earth connections. How would he test portable broadcast receivers with frame aerials, and the commercial type designed for a balanced array in which both sides are at high-frequency potential with respect to earth? Has the author had any experience with standard-signal generators, in which the whole of the generating, measuring, and attenuating equipment is in a screened box, and the receiver remains unscreened? If so, what are the faults of that type of arrangement? Passing now to Part 2, with regard to the author's definition of selectivity there are two features of a selectivity curve in which we are interested. One is the width of the flat top, and the other is the width of the resonance curve near the skirts. The width of the flat top, which governs quality of reproduction, could be given as the total width 6 decibels down from the maximum. To specify the bottom of the curve, I suggest that the lower width should be given at something like 50 decibels down from the maximum. If the curve were only some 17 to 19 kilocycles wide there, one would expect fair freedom from interference. A recent article* by W. B. Snow, of the Bell Telephone Laboratories, describes a series of tests on the range of frequencies necessary for satisfactory musical reproduction, which embodies the opinion of some 20 or 30 trained observers. Briefly, the results are that whereas audible frequencies as low as 40 cycles per sec. are produced by musical instruments, reproduction down to 60 cycles per sec. is considered to be almost perfect. The transmission of the highest audible frequencies is necessary for the perfect reproduction of sounds produced by musical instruments, mainly because of the noises accompanying the musical tones. An upper cut-off at 10 000 cycles per sec. had a slight effect on the quality of most instruments, but a cut-off at 5 000 cycles per sec. had an appreciable effect on all but the large drums. The quality of reproduction of orchestral music continued to improve materially when the lower cut-off was extended to 80 and the upper to 8 000 cycles per sec. Reproduction of the full range, which in these experiments extended from 30 to 13 000 cycles per sec., was preferred to any limitation of band width. For the reproduction of noises the highest audible frequencies were required; even a cut-off at 10 000 cycles per sec. caused appreciable reduction in the naturalness of common noises. The results seemed to necessitate no radical revision of the qualitative ideas which have been accepted by accoustical engineers for some years; their value lay rather in the quantitative corroboration which they supplied. I wish, then, to register a strong plea for a frequency range of at least 80 to 8 000 cycles per sec.

(*Communicated*): No provision seems to have been made by the author for testing receivers having an automatic volume control, nor does he specify any performance factor to cover this feature. I think automatic controls will become increasingly common on broadcast receivers in the near future. In regard to the tests and specification proposed for selectivity, these do not seem to me to cover the case of a receiver depending partly for its selectivity on the demodulation effect at the detector. This case could perhaps be dealt with by tuning the receiver to a fixed carrier and determining its selectivity by means of a second variable carrier modulated at 50 cycles per sec. as in the author's method. The audio-frequency power output resulting from this variable carrier could then be measured, and the selectivity curve plotted as is suggested in the paper.

Mr. M. G. Scroggie: Is there any particular object in selecting such a low value as 60 ohms for the output resistor shown in Fig. 2? This appears to be a rather inefficient arrangement, without a step-down transformer or other device for adapting it to the valve, and in my opinion it would be likely to encourage overloading. I should like to ask the author whether his arrangement is capable of covering, say, the medium wave-band at one sweep of the condenser. The total wave-band covered by the apparatus is very large and requires a number of coils, but whatever disadvantage this may constitute in manipulation is largely removed by ability to cover the most usual bands without coil-changing. The general practice now is to do away with screened cabins, and I should like to know whether they are really necessary in the author's equipment. In commenting on his previous paper* I remarked that in American practice only one cabin was used. American radio engineers now dispense with cabins entirely, even for signals of 1 or 2 microvolts. With regard to the method of measuring distortion, has the author tried the method of using a filter to cut out the fundamental, leaving only the harmonics? One measures first the harmonics

* *Journal of the Acoustical Society of America*, 1931, vol. 3, p. 155.

* *Journal I.E.E.*, 1930, vol. 68, p. 475.

alone, and then the fundamental plus harmonics, but with an attenuator in circuit to bring the total output to the same level in each case. The attenuator can then be calibrated in percentage harmonics. In my opinion the service areas defined (" A," " B," etc.), however suitable when first proposed, are not now representative delimitations. Only a small part of the whole gamut of field strengths existing in practice is split up into these classes, and the proposed additional area " D," which includes the aim of most modern receivers, does not quite restore the balance. A logarithmic classification is surely more in accord with modern practice. I notice that the author tests receivers without their associated loud-speakers, and in this connection I would point out that 90 per cent of present-day designs incorporate the loud-speaker in the receiver, and in many cases the characteristics of receiver and loud-speaker are complementary. I should like to know what precautions it is considered possible to adopt in order to avoid treating such receivers unfairly. I am glad to note that the author recognizes the conditions that actually exist, and fixes his upper frequency limit at 5 kilocycles per sec. Idealistic aspirations after 10 kilocycles per sec. acceptance should be reserved until international commissions have succeeded in reducing the present overcrowding of frequency channels. Turning to the method of defining selectivity, though the author rightly rejects the method which considers the ratio of response at resonance to that 5 kilocycles per sec. off tune, his objections do not apply if the frequency difference is increased to 9 kilocycles per sec.—the spacing between adjacent channels—and this ratio is much less tedious to derive than the one he advocates. In view of present tendencies in receiver design, demodulation effects should certainly be taken into consideration in assigning a figure of merit for selectivity. The author's preference for a linear power-output scale is surely contrary to all accepted practice in communication engineering. The advantages of a decibel scale are too well known to need emphasis. The definition of audio-frequency response (Fig. 8) is unsatisfactory, for this reason: a fairly level characteristic, marred by one bad resonance, would actually be much the same whether the resonance were at 400 or 450 cycles per sec.; yet widely different figures of merit would be assigned according to the plan suggested, owing to the arbitrary fixing of the datum level at 400 cycles per sec. I agree with Mr. Turner that it is almost impossible to place a useful interpretation on overall figures of merit for broadcast receivers. For my own part, I prefer the "24·9"-receiver (Table 2) to the "41·2"-receiver. Although the selectivity of the former is awarded the encouraging figure of 95·5 per cent, its selectivity is not nearly adequate for present-day conditions; while the audio-frequency response, for which the low figure of 45 per cent is awarded, is tolerably good according to commercial standards. The difficulties of rating broadcast receivers seem almost insuperable, and the author is to be congratulated on tackling the problem so boldly.

Mr. W. D. Oliphant: The subject of the paper is of vital importance to the radio industry, and I look forward to the day when a standardization committee will be formed to review the whole matter and lay down specific definitions and methods of test. American engineers have already realized the existence of this need, and their deliberations are to be found in the 1931 report of the Standardization Committee of the Institute of Radio Engineers. The compilation of a set of standards will present many difficulties, but an equally difficult task will be the setting of limits within which the tested apparatus must fall. In view of the complexity and expense of the possible tests, it will be impossible for individual manufacturers to install the necessary apparatus, and I have in mind the establishment of a central proving station whose duty it will be to carry out the necessary tests on the submitted apparatus; then, when the tests yield data satisfactory to the manufacturer concerned, they can be published and thereafter production can be checked against the standard-tested article by simple comparison tests. This proving station, which would be supported by the

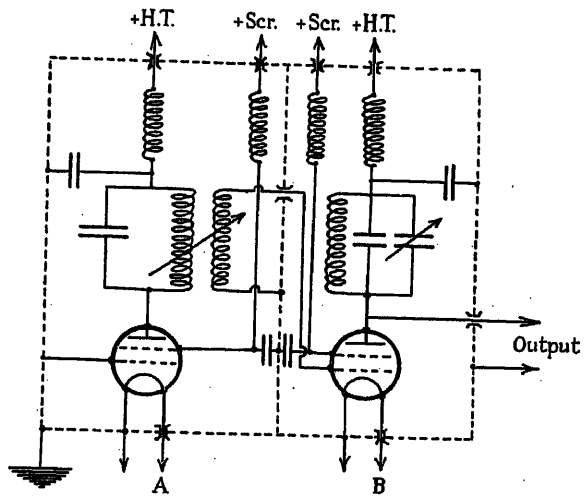


FIG. A.

industry, would also carry out research on subjects of interest to the industry as a whole. Passing on now to the paper, the author's primary object was to localize between the input terminals of a receiver a known minute modulated radio-frequency voltage. We must consider not only circuit details but also the mechanical arrangement of the entire system, as on this factor depends the elimination of a number of stray voltages whose presence would defeat the object in view. A comprehensive analysis of this question has been given by J. R. Bird.* I should like to ask the author whether he has used the dynatron oscillator as either a modulated radio-frequency or a beat-frequency oscillator. The results which I obtained some time ago on the simple dynatron oscillator confirm those recently published by F. M. Colebrook.† I further found that this type of oscillator could very easily be modulated by applying the modulation voltage to the control grid. These experiments led me to suggest the design for a beat-frequency oscillator shown in Fig. A. It consists of two dynatron oscillators A and B; A oscillates at a

* "The Design of Radio-Frequency Signal Generators," *Proceedings of the Institute of Radio Engineers*, 1931, vol. 19, p. 488.
† *Experimental Wireless*, 1931, vol. 8, p. 581.

fixed frequency, while the natural frequency of B can be varied within 10 kilocycles per sec. of that of A. Further, B is modulated at the frequency of A, so that the output from B is of the desired beat frequency: this is rectified, filtered, and amplified in the usual way. Has the author investigated any experimental methods of checking attenuator output voltages? The best method appears to be to connect two dissimilar attenuators in cascade; on increasing the attenuation of one and decreasing that of the other by the same amount, any change of output could easily be detected on a calibrated receiver. The validity of the method rests upon the fact that the two attenuators would not have compensating errors. I am very sceptical about calculated outputs, as we do not know what stray effects are present. In the case of mains receivers we are faced with another possible input, namely via the mains leads and high capacitance between the mains transformer and the rest of the wiring. Some test will have to be devised to investigate this effect, and I should be glad of the author's views on the matter. In conclusion, I would point out that the modulation percentage used by the Americans is 30, and not 40 as stated in the paper.

Dr. R. L. Smith-Rose: The first part of the paper describes the improvements and modifications in the apparatus which is in use at the National Physical Laboratory for calibrating receivers, and outlines the alterations which have been made in order to cope with modern demands. While from the description the screening may seem to be rather elaborate, it does not add in any way to the difficulties of carrying out the measurements. We have a screened cabin (a 6-ft. cube) into which an observer can get with all his apparatus, and the receiver under test is taken into a screened room of considerable dimensions; there is no difficulty in operating the whole installation. A number of problems which probably do not occur to the ordinary technical man at the works when catering for the testing of his own receivers, are introduced by the enormous range in both wavelength and sensitivity which has to be dealt with by the apparatus. Naturally its use for broadcasting wavelengths is very important, but it has also been used for testing short-wave receivers down to 7 metres, at which wavelength the apparatus behaved quite well. Turning to Part 2 of the paper, the circumstances which have led up to the development of the proposed method of specifying performance are as follows. Manufacturers and others have been in the habit of sending receivers to the National Physical Laboratory with a letter asking that these should be "tested," but without stating the nature of the test required. In replying, to put the matter on a concrete basis, we had roughly to outline the tests we proposed to make, viz. sensitivity test, selectivity test, and audio-frequency test. We never carried out one of these tests apart from the others, since the results of such a test might easily have been used to misrepresent the real performance of the receiver. We therefore had to cater for the whole series of tests, and the scheme set out in the paper was devised by the author with a view to simplifying the procedure. We hope that the proposals may perhaps serve to inaugurate a committee of this Institution or of the British Standards Institution which may in due course produce a practical specification for the testing of receivers. With regard to Mr. Turner's query as to why the author selected the 400-cycle ordinate in Fig. 8 for the definition of audio-frequency response, 400 cycles per sec. was tentatively adopted as the standard audio-frequency. In most of the audio-frequency characteristics we have come across there has been no substantial peak or dip at that frequency, so that the possible error envisaged by Mr. Turner does not seem likely to occur with the types of receivers at present available. The great advantage of standardizing the ordinate, of course, is that it does away with the necessity for calculating the mean value of every curve measured. One of the criticisms which might reasonably be levelled against the use of a band of more than 5 000 cycles per sec. is that modern receivers do not appear to take much account of frequencies above 5 000. As regards the criticism of the choice of the response curves given in the paper, I would state that Fig. 16 is the actual curve obtained from a modern commercial receiver. Taking the published response curves of three commercial receivers at present on the market, and working on the basis of the paper, I find that the audio-frequency responses of these three lie between 46 and 63 per cent. I should like to refer in conclusion to the question of selectivity characteristics. As has been pointed out, our method of recording selectivity characteristics is just the inverse of that adopted by the Institute of Radio Engineers. I do not like the inverted resonance characteristic, in the first place because it is not the type we have been used to, and secondly because it does not seem to represent the conditions as we want to know them. In talking of the selectivity of the receiver we do not necessarily want to know how strong an interfering signal must be to produce the same output as was obtained from the wanted station. The problem is rather that of determining how much output an interfering signal produces in relation to that of the wanted signal when the two incoming sets of waves are both of the same field strength.

Mr. W. J. Brown: Has the author made any direct measurements of low radio-frequency voltages as a check on the potentiometer calculations which he employs in his signal-measuring device? I have in mind that in the design of radio-frequency attenuators or potentiometers very serious errors may be introduced on account of stray capacitance currents flowing from the oscillator through the attenuator to the receiver. These stray capacitance currents produce quite an appreciable voltage-drop in the inductance and the earth-return leads, and the error may amount in some cases to 10, 50, or 100 per cent. I feel that any figure of merit for a broadcast receiver should include the acoustic performance of the loud-speaker and cabinet. It is useless to aim at an ideal audio-frequency response curve for the receiver alone, when this is liable to be entirely spoilt by the usual irregularities in response of the average commercial loud-speaker. In particular, when testing receivers employing pentode output valves it is very misleading to use a resistive load, as this takes no account of the variation in amplification of the pentode when working into a loud-speaker whose impedance varies widely with the frequency. Turning to the various

factors which contribute to the figure of merit, it seems to me that the sensitivity of the receiver is dismissed rather summarily by merely placing it in one of a number of classes. The sensitivity of a receiver often varies considerably over the wave band, particularly in the case of gang-tuned circuits. In such cases a great deal of development is often required to establish correct ganging, so as to obtain uniform sensitivity over the wave band. I think the performance of the receiver in this respect should be acknowledged in the figure of merit. As an example, a badly ganged superheterodyne receiver may have a sensitivity of 20 microvolts at 300 metres, and of 2 000 or 3 000 microvolts at 220 metres or 500 metres. On the other hand, a similar set of good design would have a sensitivity varying between 20 and 50 microvolts over the entire range. The author's suggestion that receivers should be tested at their maximum rated output seems to be subject to the drawback that when the output is approaching saturation the audio-frequency response curve will appear flatter—and therefore actually better—than it really is. I suggest a figure of one-half the rated output as being a rather more satisfactory compromise. With regard to the selectivity, the author suggests that this should be measured at constant input instead of constant output, but I do not feel that this gives the kind of comparison we need. The purpose of a selective receiver is to receive signals of the order of 0·1 mV per metre from a distant station the frequency of which is spaced only 10 or 20 kilocycles per sec. away from that of a local station giving a signal strength of 100 mV per metre. The input thus varies in the ratio 1 000 : 1. The output, on the other hand, is naturally adjusted by the user to a more or less constant value, sufficient to give a comfortable volume of sound in his room. Thus we can only simulate the actual conditions of listening if we test with constant output and vary the input accordingly. A further point is that if we have a curve of output at constant input we get the sort of thing the author depicts in Fig. 13. If we wish to find how many kilocycles per sec. we have to detune in order to decrease the response 1 000 times, so as to get the conditions of receiving a distant station from a point close to the local transmitter, the scale of Fig. 13 becomes so small as to be unreadable; in fact, the lowest output we can estimate from Fig. 13 is 10 milliwatts, which corresponds to only $\frac{1}{50}$ the peak output or $\frac{1}{7}$ the peak output voltage. A sevenfold reduction in voltage is very small compared with the 1 000 : 1 ratio which actually exists between the signal strengths of the local and the distant station, and it is impossible to say from Fig. 13 how far it would be necessary to detune the receiver from the local station before a distant station could be received (it looks as though it would be of the order of 100 kilocycles per sec.). I should like to refer to the high figure of 95·5 per cent which the author gives for the selectivity of the arrangement shown in Fig. 13. This is obviously not a very selective receiver, as nearly 100 kilocycles per sec. detuning is necessary for a 1 000 : 1 ratio, and in a modern receiver of the superheterodyne type it is only necessary to detune 10 kilocycles per sec. to allow for the same ratio. In other words, modern receivers can be produced having 10 times the selectivity of the arrangement shown in Fig. 13, and the figure of merit of 95·5 which has been allotted to this receiver does not give sufficient scope for improvement.

Mr. L. B. Turner: Many of the previous speakers have referred to the undesirability of an omnibus figure of performance for a broadcast receiver, and I thoroughly agree with their objections to such a figure. Also, one of the three terms upon which the figure of performance is based is selectivity, and I should like to criticize the manner of defining this which is explained in Fig. 7. The method adopted by the author leads to the selectivity being expressed as x/y, where x and y are respectively the areas CDEF and CKLD. These areas approach equality as the selectivity approaches perfection. I think it would be preferable to measure the small difference of these two nearly equal large quantities, and perhaps define the selectivity as $y/(y-x)$. The unrejected residuum has to be dealt with, and there is a practical 2 : 1 relation between two receivers whose selectivities the author would express as 99 and 98 per cent.

Mr. A. H. Cooper (*communicated*): To what does the author attribute the presence of 10 per cent of harmonics in the output of his 3- and 4-valve sets even near zero output? Is it due to impurity in the low-frequency oscillator, or in the modulator, or does it originate in the detector of the receiver? I cannot understand why his method of measuring selectivity is more representative than that adopted by the Institute of Radio Engineers. The author's method gives the product of the ordinate of the resonance curve and the detector efficiency at the correspondingly decreased input. Thus, in two similar receivers, one with a square-law and the other with a linear detector, his method will give a better selectivity figure for the square-law detector, whereas it is common knowledge that, owing to demodulation, the linear detector is the better. This is quite in addition to the difficulty already mentioned by another speaker of measuring the output to a sufficient attenuation to be of any use. It is idle to suggest that this curve represents actual fact: in practice the set is used to receive a wanted signal in the presence of a neighbouring unwanted one. The wanted signal will load the detector so that its efficiency is that of the centre of the scale, and its changes at other inputs do not concern us directly. I can see no way of stating the selectivity of two widely different receivers except in terms of two inputs, representing the wanted and unwanted signals. A trivial point in the proposed standardization scheme is the division between the medium-output class (3) and the large-output class (4) at 1 watt. The output of many typical 3-valve mains sets ranges from 0·8 watt to 1·2 watts: some of these sets will fall in one class and some in the other, whereas in point of fact they are all very similar. I suggest that the point of division should be raised to 1·5 watts. Finally, I should like to utter a word of warning against the apparent safety of elaborate screening. A radio-frequency generator of large dimensions (and the author's is of a very large size) is difficult to check; its output is often only partly controlled by the attenuator. The voltage-drop in the various earth paths is considerable and cannot be checked completely by varying the

attenuator ratio and current in opposition. The laboratory where I work has in the past 2 years abandoned the use of large screens in favour of rational screening of small size, in which earth paths can be isolated and allowed for. By this means a generator can be made to work in a week instead of 6 months. A large generator in a screened room often gives less accurate results than a small portable generator, which is so easy to use and cheap to make or buy that it will be used throughout the design of a receiver, and the product will be better in consequence.

Mr. R. H. Nisbet (*communicated*): If, for a measure of audio-frequency response, a quantity is required which will be unity for perfect response, why does the author not choose the ratio of the unshaded area *under* the response curve of Fig. 8 to the area ABCD? Is the reason that the figure so obtained would be too near to unity for all receivers, so that the worst receivers would appear to differ by too little from the best? If this be the case the construction of the author's formula, with its arbitrary constant K, may well be justified. Why not extend the principle to the definition of selectivity, where the author's plan gives high figures of merit even for very unselective receivers? I should like to propose that the level of the line BC of Fig. 8 should be that of the highest peak. This would have the undoubted merit of penalizing receivers with the narrow and very peaked type of resonance curve, which is often associated with the combination of receiver and loud-speaker. In view of the possibility of demodulation of one received signal by another, a subject on which the last word has not yet been said, is it legitimate to define selectivity in terms of unmodulated waves? The definition of selectivity must be based upon the nature of the audio-frequency output when the receiver is tuned to a modulated transmission while subjected to interference from other carriers—modulated and unmodulated. At what level of retroaction would the author test a receiver for selectivity and audio-frequency response? There is still scope for considerable variation inside one of the type classifications, especially in type "D." Who would classify the receiver—the manufacturer or the tester? How would a receiver be tested which was claimed to be suitable for all four service areas? As regards the numbering of the classes, I think a system should be avoided in which a 3-valve mains set might be classified as "C3," while a simple crystal set might be described as "A1."

Dr. E. H. Rayner (*communicated*): The paper deals with a subject of considerable public as well as technical interest. There are many cases in which receiving sets of the more powerful and expensive types are installed in churches, schools, and village institutes. The people responsible for choosing such apparatus have very little to guide them, except perhaps the advice of friends or a certain amount of experience of one or two receivers which will generally be obsolescent owing to rapid progress in methods of operation, new design of circuits, valves, and loud-speakers. From a manufacturer's point of view the amount of advertising is in such circumstances probably as important as quality as an aid to selling apparatus. It would obviously be much easier to spend money wisely if a graded standard of performance were instituted. The question as to what type of receiver should be installed in any given instance depends upon the distance of the particular locality from the wanted station. In this country there are some 10 000 schools which are potential users of good-quality receiving sets. At present probably less than one-quarter of these are provided with receiving equipment, and much of the apparatus now in use is not up to the present-day standard. A recognized scheme of type-testing such receiving sets would not only be helpful to those who are entrusted with expenditure of money of a public character, but it would also be a valuable educational influence for both manufacturers and users of equipment. Several speakers have mentioned the desirability of including tests up to a frequency of 8 000, and it seems that even the most experienced radio engineers have little definite knowledge of the frequency characteristics of commercial receiving sets. I agree with the author that there is little object in testing at 8 000 cycles per sec. if practically nothing of such a frequency is included in the output. The results of a type test, even if as is desirable to begin with—the standard of performance required is a low one, cannot fail to be of valuable assistance to both the user and the manufacturer. Type tests would help to create a demand for good-class equipment. One such test would probably cost less than a page of advertisement space, of which several are taken in the weekly and monthly Press by many firms.

Mr. P. G. A. H. Voigt (*communicated*): The paper suggests standards which may be difficult to change once they have been generally adopted, and it is therefore desirable to examine any possible alternatives to them. I think that a wider frequency scale should be adopted. "Grasshopper" noises are greatly reduced by eliminating frequencies in the immediate neighbourhood of 9 000, so that a system cutting off sharply at 8 000 will exhibit but little of this class of interference, while retaining a clarity which cannot be obtained with a system cutting off at 5 000 cycles per sec. With regard to classification, I suggest that the number should be placed first and the letter last, for according to the author's system a "C3" set is better than one classed as "A1." I am glad to see that he includes the "purity factor," which becomes increasingly important as the frequency scale is improved. I suggest that this should also be measured at a lower frequency than 400, say at 100, as a measurement at 400 cycles per sec. may not disclose whether the output choke or transformer is capable of handling a strong, low note without introducing serious hysteresis or saturation distortion. In my opinion the percentage fault should be stated rather than the percentage perfection. An unscrupulous salesman could easily persuade the gullible public that the difference between his set, which is 95 per cent selective, and a rival set with a selectivity of 99 per cent, is too small to make any difference. If these two sets were described respectively as 5 per cent and 1 per cent non-selective, this would not be so easy. I consider that the selectivity and response curves should not be drawn on a power scale, but on either a voltage or a decibel scale, using suitably modified values for K. I agree with Mr. Turner that it is undesirable to make use of a fixed frequency in order to obtain the height of the rectangle ABCD (Fig. 8) for the low-frequency

response figure; the mean of two octaves, say from 250 to 1 000 cycles per sec. or from 500 to 2 000 cycles per sec., would be easier to estimate (and more appropriate) than the mean over the whole scale. The question of including the loud-speaker in the calibrations has been raised, and I think that this should be done when the set is intended to be used with a particular loud-speaker, but the figures should be stated separately. The total forward sound radiation can be obtained with sufficient accuracy by taking three response curves, one on the centre line, one 30°, and one 60° off the centre line, and "weighting" the results according to the area which each belt represents. With suitable gear, a response curve covering the whole scale can be drawn automatically in less than 3 minutes; thus the three curves can be drawn and the total result estimated in less than ½ hour. Whether the purity factor of the loud-speaker should also be measured is a matter for debate. The author's apparatus for purity-factor measurement, together with the microphone and amplifier used for the response measurement, should be satisfactory for this purpose. If this latter test is to be of any value it should be made at several different frequencies.

Mr. H. A. Thomas (*in reply*): Mr. P. K. Turner points out that the specification may give a better overall figure for a receiver having a poor sensitivity than for a receiver having a much higher sensitivity, and he says that he personally would prefer the more sensitive receiver. He also states that the question of which is the better of two receivers is determined by the needs of the particular user. That is precisely what the suggested classification does, in so far as it permits of comparative analysis being made between two different receivers. Doubts may arise as to the feasibility of an overall figure of merit, but I cannot see where the suggested specification fails to bring to light the relative properties of receivers. The field-strength classification is essential if tests are to be made with any rapidity, and it appears to me to be the only method of obtaining comparative results. Results of selectivity, audio-frequency response and purity factor, given for all sensitivity settings of a receiver, would be so cumbrous as to be worthless for quick-comparison purposes. The field-strength figures are adopted as a result of measurements on broadcast transmission-service areas, and they cater for the majority of receivers designed to operate within these areas. Mr. Turner regards the highly selective and sensitive receiver as the normal type, whereas I consider the receiver designed for use within a service area to be more representative of the average present demand.

Several speakers refer to the upper audio-frequency limit of 5 kilocycles per sec. as being too low. I agree with Mr. Barton that a cut-off at 5 kilocycles per sec. does definitely detract from the reproduction of much orchestral music and speech, but I maintain that this upper cut-off figure is governed by the international frequency allocation and that, so long as this is as low as 10 kilocycles, there is no merit in aiming at anything higher. Furthermore, the remarks of Dr. Smith-Rose show that few commercial receivers give a response at frequencies above 5 kilocycles per sec.; hence the limitation is more academic than practical with present designs.

Mr. P. K. Turner suggests that the line BC in Fig. 8 should represent the mean of the area and not the value at 400 cycles per sec. In the original specification this was done, but it involved the calculation of this mean value for each curve. Since our experience was that no receiver tested showed any marked resonance at 400 cycles per sec., we found that the difference between taking BC as a mean value and as the value at 400 cycles per sec. was so slight as not to justify the extra labour involved in computing this mean value; and, since it was desired to make the tests rapid, the 400 cycles per sec. value was adopted. I agree that a decibel scale would be preferable in this case. I cannot agree that all the receivers tested were bad—they were submitted for test as being distinctly better than most, and in fact were suggested as being patterns upon which a limiting specification could be drawn. With reference to Mr. Turner's remarks on Section (1) of the paper, I will give the following information regarding the valves used. The oscillator and modulator valves may be any small power valve such as the P240, and the output valve is a fairly large power valve such as the LS6A. The coupling condenser between the oscillator and the modulator, together with the bias of the modulator, are so adjusted as to give a linear relationship between the anode voltage of the modulator and the output current, and it is found that these values are not critical and, if once set, remain valid over a very large working frequency-range. The variation in frequency by means of a variometer inductance is a helpful suggestion, but is not quite so convenient in practice as a variable condenser. A linear modulation meter could be used, but is not suitable in the present case, since a much larger input would be required and a linear modulation meter can only be operated up to 70 or 80 per cent modulation. There is no difference in operating behaviour and accuracy, and, owing to the greater sensitivity of the square-law meter, it was adopted. There is nothing more to add to the information given in the paper regarding the details of the attenuator, which was fully described in my previous paper (*loc. cit.*). Capacitance effects to the screen were made small by careful calculation, and checks have been made to demonstrate that these potentiometers give reliable results at frequencies as high as 30 000 kilocycles per sec. The difficulty with a valve voltmeter as the final instrument upon which the accuracy of the measurement depends is, that for small currents the series resistance across which the voltage has to be measured must be large, which involves uncertainty at very high frequencies. It was more convenient to make this final measurement in terms of current, and, since such a current measurement is probably more accurate and requires no auxiliary apparatus, it is preferable to the valve-voltmeter method. The bridge described in the paper for measuring harmonics may be used to pick out individual frequencies if desired; but, if this were done, the measurement would become very involved and it is doubtful whether the information so obtained would be of much value in a specification. Grouping of the harmonics forms a simple means of assessing distortion, and is adopted in American specifications.

In reply to Mr. Barton, cabin A is 12 ft. × 8 ft. × 9 ft. high. For the testing of frame-aerial receivers, a small series resistance is inserted, the input e.m.f. being applied across this and a calculation made to allow for the slightly increased frame resistance. Similarly, if no earth connection is provided, a balanced condenser-system can be attached to give the required signal e.m.f. This has been done at 40 000 kilocycles per sec. when testing a short-wave frame direction-finder. Standard signal generators give a fair degree of accuracy, but the equipment described in the paper must obviously be superior in performance since it can be used to calibrate such signal generators. Although quite satisfactory for their purpose, much has to be sacrificed for portability and robustness. The apparatus described in the paper can readily be used for testing receivers having automatic volume controls. The reply to Mr. Barton's remaining remarks is contained in my reply to Mr. Cooper.

Mr. Scroggie raises the question of the value of the output load of 60 ohms. This value is determined by the attenuator network, and for the ratios used 60 ohms was a suitable load. One does not build an attenuator to match a valve, but to have as low a resistance as possible to give the required voltage range. High-resistance attenuators should be avoided at high radio frequencies owing to the difficulty of self-capacitance effects. The coils are chosen to have an inductance such that a maximum wavelength change can be covered on each range. Regarding the use of two cabins, the function of cabin A is to render outside field strengths negligible, and that of cabin B is to screen the oscillators effectively. Although, no doubt, some simplification of these screens could now be effected, it must be realized that the apparatus was built for many purposes other than testing broadcast receivers; unscreened apparatus may therefore have to be erected quickly in the large screened cabin B. This is quicker than building a complete screened set for every special measurement required. Mr. Scroggie's remarks on the harmonic bridge seem to be superfluous, as they describe what is done in the present bridge. His remarks on service areas show that he is thinking of a special type of sensitive receiver and not of a typical broadcast receiver designed for use within a service area. Regarding the testing of receivers without their associated loud-speaker, I have repeatedly urged that this type of comprehensive overall measurement is desirable, but a strong feeling has hitherto existed that a receiver should be designed to operate any loud-speaker and that compensation should not be resorted to. I prefer such an overall measurement and would welcome a request to test receivers in the manner suggested, by adding acoustic measuring apparatus to the existing electrical gear. I notice with pleasure that Mr. Scroggie agrees that at present a 5-kilocycle upper frequency limit is imposed by the present frequency allocations. The remaining points which he raises are dealt with elsewhere in this reply.

I am glad that Mr. Oliphant appreciates the object of the paper, namely, to stimulate interest in the standardization of test procedure. Regarding his remarks on the dynatron oscillator, I would point out that certain rough tests have been made on it and that this type of circuit appears to be quite satisfactory. The testing apparatus was constructed, however, before this work was completed and hence the dynatron oscillator has not been used. Doubtless, if more work were done, the dynatron oscillator might be shown to be preferable to the present triode generator. I am indebted for his correction of my figure of 40 per cent modulation.

I thank Dr. Smith-Rose for his remarks, which do not call for any reply but add useful information to the paper and in themselves answer several points raised by speakers.

I have already partially answered the point raised by Mr. Brown in regard to checking the attenuator at high radio frequencies. I would add, however, that it is possible to establish the accuracy of the system by cross-checking on various attenuator settings with different current values and at different frequencies. The results of numerous such tests establish the fact that the order of accuracy of the present design is well within 1 per cent. I have already replied to the point as to testing the receiver with the loud-speaker. The next point raised by Mr. Brown is covered by the sensitivity classification. If the ganging were bad, the receiver would not give satisfactory results in the particular class in which it gave optimum results, and it would have to be classified separately for different wavelengths. This would immediately demonstrate its failings as regards sensitivity. The necessity for testing at the maximum output is due to the fact that all tests must be made with some definite signal; and since one of the tests, viz. purity factor, demands maximum output, it is preferable to maintain this output for all the other tests. I disagree with Mr. Brown as to the best method of testing selectivity. The case cited is not normal but is obtained when a receiver is used to receive a weak signal in the presence of an interfering strong signal. This condition is important in assessing the properties of a powerful and selective receiver, but for the vast majority of receivers the interference is not greater than the desired signal. Hence, if the output obtained at the desired frequency is known, and the output at some frequency removed slightly from the desired frequency is also known for the same setting of the receiver, this information enables a precise picture of the operating conditions to be made. The introduction of a suitable numerical coefficient in the definition of selectivity meets Mr. Brown's final criticism; such a coefficient would be determined by a Standards Committee.

I am inclined to agree with Mr. L. B. Turner that the method which I have adopted of defining selectivity does not sufficiently grade performance. A suitable numerical coefficient would, however, be preferable to expressing a poorly selective receiver by a higher figure than a good receiver. I am afraid the latter method would lead to confusing results, particularly from the advertisement point of view.

In reply to Mr. Cooper, the harmonics which are always present are almost certainly due to the detector. It would be nearly impossible to test selectivity in the manner suggested. If two signals were imparted to the aerial system and the wanted and unwanted signal were varied in value and frequency over a range commensurate

with actual working conditions, the mass of results would be prohibitive. Admittedly, selectivity does in practice depend upon the precise method of excitation, but any specific conditions can be obtained by calculation from the simple selectivity characteristic suggested. I cannot see how a poorly designed portable generator can give results superior to those with a generator in which every point has been most carefully examined and where efficiency and precision have not been sacrificed for portability.

In reply to Mr. Nisbet, I prefer to take the line BC at the mean value or at some mean frequency such as 400 rather than at the peak value, as the latter method would not differentiate between a receiver with a sharp resonance at some frequency and one in which the resonance rose to a high value over a large band width. The point in regard to selectivity has already been answered in my reply to Mr. Cooper. The manufacturer would classify the receiver, and the testing laboratory would give figures for that class, or, alternatively, the laboratory could give figures for more than one sensitivity class. I am inclined to agree that the numbering and lettering could be improved. Naturally, these points are all open to discussion.

The encouraging and helpful remarks of Dr. Rayner are welcome. It must be realized that many of the suggestions put forward by several speakers would involve a prohibitive amount of testing, and the results would probably be of little practical value. The problem which I have attempted to solve is that of providing a simple test schedule to act as a basis for discussion, and although in detail it may be subject to many academic criticisms, I maintain that the essential points do form a definite criterion of receiver performance upon which present-day receivers could be approximately graded according to their relative effectiveness.

Most of the points raised by Mr. Voigt have already been answered. I am not very favourably disposed towards a system of merit figures which inverts the performance. A more steeply graded system is possibly desirable, but I feel that the perfect receiver should be assessed as 100 per cent and not zero.

DISCUSSION ON "A METHOD FOR DETERMINING THE EFFECT OF THE EARTH ON THE RADIATION FROM AERIAL SYSTEMS."*

Mr. J. A. Ratcliffe (*communicated*): In Section (1) the author remarks that the Fresnel reflection formulæ are only valid provided that the point of observation is not close to the surface of the earth. Both theoretical and experimental considerations lead me to believe that this proviso is unnecessary, and, provided only that the incident waves are plane and are incident sufficiently steeply, the Fresnel reflection formulæ will give the correct result, even when the field is measured just above the ground surface. The theoretical deduction of the reflection coefficients, either by the boundary-condition method of Fresnel, or by the method of Darwin,† does not seem to indicate any breakdown of the theory, even at distances less than one wavelength from the surface. I think that we have experimental confirmation of the theory in some experiments described by Barfield.‡ He tested a loop receiver situated near the surface of the ground, using an elevated transmitter as a source of downcoming waves, and he found that his results agreed with theory when the effect of the ground was taken into account. I believe that this effect was calculated by using Fresnel's reflection coefficients, although this is not expressly stated in his paper. The wavelength used was 21 metres. I am especially interested in the very elegant explanation of the shadow effect observed by Barfield and Munro, and I should have liked a little more information as to the exact method of calculation of the theoretical curves of Fig. 4. How was the image effect of the lower portions of the re-radiating aerial calculated? There is reason for believing that the Fresnel formulæ do not give the correct result when the incident ray is very close to grazing incidence. This introduces difficulties in integrating all along the re-radiating aerial, and I should like to know how they were overcome. I imagine that the resultant field (incident + re-radiated) will vary, both in magnitude and in phase, up the final receiving aerial. Is the field represented in Fig. 4 some kind of mean value?

Dr. L. C. Verman (*communicated*): In the first section of the paper the author refers to some of my work and suggests that the discrepancies between the reflection theory and my measurements close to the surface of the earth were due probably to the proximity of the ground rather than to that of the various objects, stray reflections from which could easily mar the accuracy of the measurements. I pointed out in some detail the reasons for my belief.§ The author, however, does not give reasons for his criticism. He agrees that the reflected ray can be considered to be due to the currents set up in the earth by the incident ray. I clearly stated this view in my paper (*loc. cit.*, p. 1400)

* Paper by Mr. J. S. McPetrie (see vol. 70, p. 382).

† C. G. Darwin: *Transactions of the Cambridge Philosophical Society*, 1924, vol. 23, p. 137.

‡ R. H. Barfield: *Journal I.E.E.*, 1930, vol. 68, p. 1065.

§ *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 1422.

and pointed out the error on the part of some workers who considered that the earth currents could have an effect additional to causing the reflected wave, although no such effect has been specifically calculated or experimentally observed. Hence it is clear that the mere proximity of the ground cannot be held responsible for the discrepancies observed. Perhaps the author has in mind the effect of the non-planar character of the wave front, which he rightly thinks will cause errors in the neighbourhood of the radiating antenna. However, such conditions do not apply to my observations. I was studying a wave radiated from a station some 250 miles away. The wave-front was found to be essentially plane and the polarization elliptical.

Mr. J. S. McPetrie (*in reply*): I am indebted to Mr. Ratcliffe for his interesting comments on the ray theory of reflection. Fig. 4 in the paper was deduced by integrating the effect of the dipoles in the shadow aerial at one point in the receiving aerial. This would lead to a little inaccuracy. The problem at the moment was not, however, to deduce from Mr. Barfield's experiments the electrical constants of the earth but to show that when reflection of the waves at the earth's surface was taken into account the experimental results could be explained by the ordinary theory. Fresnel's formulæ were used to determine the amplitude and phase of the wave reflected at the earth's surface; but since the calculation was made I have come to the conclusion that the conditions at the receiver were such that the formulæ could not be applied accurately. This inaccuracy is such that the conductivity calculated by Fresnel's equations would be smaller than the true value. This idea is corroborated by experiments made by Dr. Smith-Rose and myself, which indicate that at the frequency used by Mr. Barfield the conductivity would have a value several times the values given in Fig. 4. Mr. Ratcliffe suggests that Fresnel's formulæ are accurate, when the receiver is close to the earth's surface, so long as the wave reaches the earth with a sufficiently small angle of incidence. I can see no theoretical reason for this limitation. If Fresnel's formulæ apply to a receiver close to the earth and with small angles of incidence, they must apply under the same conditions with large angles of incidence. I suggest that the obvious errors introduced when using Fresnel's formulæ to find the field at points near the earth's surface are due to the fact that they apply only to plane waves. If the receiver is near the earth the re-radiation from the earth's surface cannot be considered to be plane at the receiver (i.e. both the main and the reflected waves at the receiver must be plane). The distance at which the formulæ cease to be applicable is difficult to determine, but, as suggested by Mr. Ratcliffe, it is probably less than a wavelength. If Mr. Barfield could be induced to repeat his kite experiment for different heights of the kite transmitter, we should obtain valuable information as to the applicability of the ray theory at high angles of incidence.

Dr. Verman has apparently misunderstood my explanation that one might expect discrepancies between experiment and theory (using Fresnel's equations) in investigations such as his when making measurements of the field strength near the earth's surface. The wave reflected from the latter is due to the currents set up in that surface by the incident wave from the transmitter. Fresnel's equations give the magnitude of this field at points distant from the reflecting surface such that the field from these currents may be considered to be plane at the receiver. When the receiver is very near the earth Fresnel's equations cannot be used, as this condition is not fulfilled. For this reason I suggested that Dr. Verman might expect discrepancies when he applies Fresnel's equations to find the field at points near the earth's surface. Dr. Verman admits that errors would occur if the equations were applied near the radiating antenna, but he states that in his case the transmitter was 250 miles away. He forgets, however, that there are really two sources of radiation—the transmitting antenna and the earth, owing to the currents set up in the latter by the plane incident field from the transmitter. Dr. Verman is inconsistent, therefore, when he will not admit the discrepancies due to the proximity of this second radiator, the earth. In the paper the radiation from the earth's surface is not taken into consideration twice. I have considered, first, the plane wave from the transmitter, and secondly the wave (the reflected wave) radiated from the earth's surface. I do not suggest that all the discrepancies which Dr. Verman found are due to this effect. Neighbouring objects probably did play an important part, but what I state in the paper is that one might expect discrepancies even without any disturbance due to neighbouring objects.

THE ATTENUATION OF SHORT WIRELESS WAVES AT THE SURFACE OF THE EARTH.*

By G. H. MUNRO, M.Sc., Associate Member.

(*Paper first received* 18*th May*, 1931, *and in final form* 9*th January*, 1932.)

SUMMARY.

An apparatus is described for measuring relative field intensities of wireless waves of the order of 20 metres, and the results of a series of measurements taken with it on wavelengths of approximately 25 metres for distances of from 200 ft. to 60 miles from the transmitter are shown as "Intensity/Distance" curves. For distances greater than 2 miles the decrease of intensity is found to be approximately proportional to the inverse square of the distance as predicted by the theory of Sommerfeld. For shorter distances, however, the curves are much straighter than predicted by theory. This is attributed to penetration of the waves to layers of higher conductivity below the surface. This is supported by the increase in the variations in attenuation with change of surface observed on a wavelength of 18 metres and by measurements on the "tilt" of the electric vector of the wave-front.

In all cases, marked changes in intensity and attenuation were found to occur with apparently slight changes of surface and slope of the ground.

INTRODUCTION.

Attention was drawn to Sommerfeld's theory of the propagation of wireless waves over the earth's surface by a paper by Smith-Rose and Barfield† in which some of the mathematical expressions were reduced to forms more suitable for numerical calculation. The theory was later tested by Barfield,‡ and independently by Ratcliffe and Barnett,‖ and found to be substantially in agreement with observed conditions. Further observations of attenuation on broadcasting wavelengths have since been made in various countries by different workers, but little has been published on attenuation on shorter wavelengths. It is desirable that the theory should be checked over as great a range of wavelengths as possible, and particularly for the shorter waves which have come into such prominence of late years. The following investigation was therefore undertaken to obtain attenuation curves for wavelengths of the order of 20 metres.

As it is much easier and more accurate to take measurements on a steady carrier wave than on telegraphic transmission, 5SW, the experimental short-wave station of the British Broadcasting Corporation at Chelmsford, then on a wavelength of 24 metres, was selected as the most convenient source.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Reference (1). ‡ *Ibid.*, (2). ‖ *Ibid.*, (3).

THE MEASURING APPARATUS.

The first receiver developed for the purpose was an adaptation of one which had been used for intensity measurements on the broadcast band of wavelengths. An oscillating detector tunable to the required high frequency was coupled to the tuned grid circuit of this receiver, producing, in effect, a supersonic heterodyne type of receiver. The essentials of the circuit are shown in Fig. 1. The Hartley circuit was used for the oscillating detector, the tuned grid circuit of the intermediate

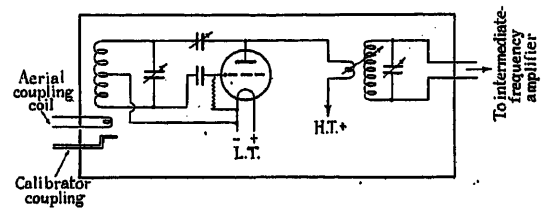


FIG. 1.—High-frequency unit of short-wave receiver.

frequency being coupled to the high-frequency choke. An untuned aerial was used, loosely coupled to the oscillating coil. The recording galvanometer was in the anode circuit of the second detector valve, which was an anode-bend rectifier.

A calibrating oscillator was also loosely coupled to the grid coil of the first detector. The circuit of this oscillator is shown in Fig. 2. It also is a Hartley circuit. The thermo-junction heater is connected in the

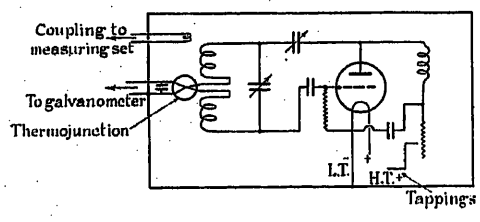


FIG. 2.—Calibration oscillator.

centre of the oscillator coil, and one of the couple leads is earthed directly to the screening box to minimize leakage of the high-frequency current along the galvanometer leads. The anode H.T. voltage could be varied by tappings and by a variable series resistance to give a continuous range, and with the microammeter in use on the thermo-couple a workable intensity ratio of 10 to 1 was obtainable. To increase this either the thermo-junction or the coupling coil was changed. In

a later modification, a small, enclosed, brass shunt-box was incorporated in the screened lead to the receiver, and with three values of shunts the range could be extended to 100 to 1. As the oscillator output to the receiver was varied mainly by reducing the current in the tuned circuit of the oscillator, the ratio of signal received by leakage to signal via the coupling was constant. It was easy to ensure that it was sufficiently small. A copper lid with flanges fitting closely inside the box and clamped to it by screens was quite satisfactory. The thermo-junction was calibrated on direct current and the calibration was assumed to hold for the high frequency (remembering that we are concerned with relative values only).

This apparatus was installed in a motor van. A telescopic aerial of aluminium tube could be projected through the roof, and a counterpoise was run down both sides of the van outside, close to, but not touching, the sides. In taking an observation the station was first tuned in and the deflection noted. The grid circuit was then mistuned just clear of the station, and the calibrator was tuned in and adjusted to give the same deflection. The difference in tuning was not enough to cause an appreciable error.

After the 1928 observations on 5SW the apparatus

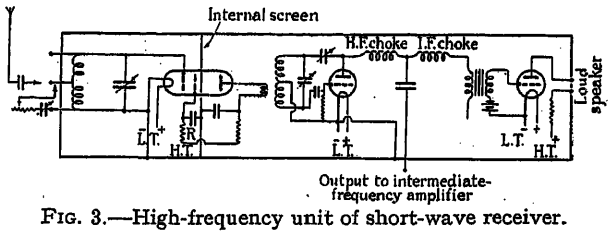


FIG. 3.—High-frequency unit of short-wave receiver.

was reconstructed to improve both the sensitivity and ease of control. A screened-valve high-frequency stage was used, transformer-coupled to the oscillator-detector, and a supersonic unit tuned to about 3 000 metres for the intermediate frequency. The circuit of the high-frequency part of the apparatus is shown in Fig. 3.

The aerial was connected through a condenser of small capacitance to the centre point of the tuned coil in the grid circuit of the screened valve. This was found entirely to eliminate stray body-capacitance effects unless the aerial were approached very closely. (The set was, of course, completely enclosed in a metal-covered box.) A variable condenser of very small capacitance was connected in parallel with the main oscillator condenser for fine tuning. This, as well as the main condenser, was fitted with a slow-motion dial, so that excellent control of tuning was obtained over a wide range of wavelengths. The main condenser motion was sufficiently slow for "searching," and the station, once heard, could be tuned in very accurately with the smaller condenser.

A capacitative coupling was used to the intermediate-frequency amplifier, which allowed of better choking in the detector anode, resulting in a smoother control of oscillation at the threshold. This was of importance as the high-frequency unit, which is a complete short-wave receiver in itself, was used alone without the intermediate-frequency unit for measuring very strong signals. By means of plugs and jacks the indicating galvanometer could be plugged in to either the first or second detector anode circuit. This galvanometer was fitted into a screened box with a series of shunts and an arrangement for "backing off" the steady anode current if necessary.

It was later found that greater sensitivity could be obtained by using as intermediate frequency a "two screened-valve portable receiver" tuned to the longer-wave band, the high-frequency unit providing a sensitive and convenient "short-wave adaptor." For measurement work such a receiver was adapted suitably and enclosed in a screening box. The receiver thus produced was very sensitive, but easy to control, free from stray capacitance effects, and constant in use. The requisite batteries were either fitted inside the box with the receiver or provided with a separate screened box and connected by screened leads. In the latter case it was found convenient to include in the various H.T. leads suitable resistances so that only one value of H.T. voltage was necessary.

The calibrator was permanently coupled to the first tuned coil. When using the calibrator the aerial was disconnected and replaced by a compact equivalent circuit consisting of a small, screened, variable condenser and a non-inductive variable resistor of a few ohms in series with it connected between the earth end and the centre-point of the coil. The values of capacitance and resistance were adjusted to give the same effect as the aerial itself. The pick-up on this "dummy" aerial was very slight, but actually there was just enough to produce an audible heterodyne between the station and the calibrator, and this was found useful in checking the tuning.

For long-distance work the apparatus was installed in the motor van with a telescopic aerial as before, but a counterpoise was not necessary with this coupling. Tests were carried out to see whether there was any directional effect due to the van, but it was found to be negligibly small. For shorter-distance work on a local transmitter the apparatus was mounted on a wooden frame on wheels.

In all the above receivers it was possible to listen on a loud-speaker or headphones to the transmission without disturbing the measurements. It is of great advantage to be able to hear the signals that are being measured, and to know that they are free from interference and undue modulation fluctuations.

For the short-distance observations a small portable transmitter was constructed. A PM252 valve was used in the circuit shown in Fig. 4. To the oscillator coil was loosely coupled a split aerial coil with plugs for connecting a thermo-couple heater in the middle. The contact type of thermo-junction was used, with one of the couple leads connected to the metal screening box so that the middle of the aerial coil was effectively connected to the box. Leads from this coil were taken out of the box to the telescoping aluminium tubes which served as aerial and counterpoise. Generally the aerial was vertical and the counterpoise horizontal, with the coil connected to its mid-point. The complete oscillator and the aerial coil were enclosed in a copper

" plymax " box so that radiation took place from the aerial system only. Leads were taken out from the thermo-couple to a suitable microammeter, one of these leads being connected to the box, as mentioned above, and a 1-μF condenser was placed across them to bypass any stray high-frequency currents. Screened leads were taken to the batteries in another screened box. The whole apparatus was mounted on a wooden stand with the aerial system fixed on a block of ebonite. The aerial was tuned to the required frequency by choosing a suitable number of turns for the coupling coil and then adjusting the lengths of aerial and counterpoise until the maximum deflection was obtained on the thermo-junction galvanometer. With a range of 4 thermo-junctions measurable currents of from 1 to 800 mA could be obtained in the aerial, so that the apparatus was very convenient for checking the receiver calibration. Modulation for speech was provided by including in the anode circuit a 2 000-ohm resistance which was also in the anode circuit of the second valve of a two-stage low-frequency amplifier working on a microphone. This worked quite well on all the wave-lengths and was found very useful.

The receiver was checked against the transmitter for

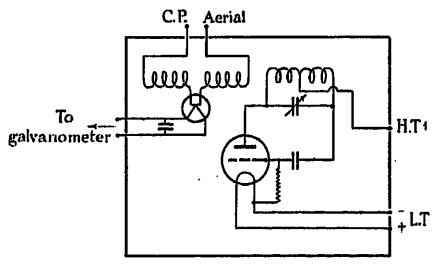


FIG. 4.—Transmitter circuit.

relative strength of signals. The agreement was within 5 per cent for the intensity range used, which was quite satisfactory for the work.

OBSERVATIONS OF 5SW.

The first run was taken in a westerly direction over ground with slight undulations but of a fairly uniform average level and with few trees. These conditions hold for some 12 miles until Epping Forest is reached. Observations were tried within the forest but the signals were too weak for measurement.

A further run was then taken more to the northward where the distance could be extended to 20 miles, but the ground at that distance became more uneven and the signals too weak for accurate measurement. This was partly because of the presence of a marked shadow, apparently due to the masts supporting the 5SW aerial. The signal strength in the line of the masts was only one-quarter of its value at the same distance in a direction 30 degrees more to the southward, the change being gradual.

The results of these two runs are shown in curves I and II of Fig. 5. The intensity is plotted against the distance from the transmitter in miles. Logarithmic paper is very convenient for the purpose as it allows the intensity scale to be changed by any multiple without affecting the shape of the curve. In Fig. 5 the intensity scale is the same in both cases, the difference in the intensities for the two curves being due to the mast shadow. The dotted lines represent average curves through the points. It will be seen that up to 8 miles the points lie fairly smoothly about the average, but beyond that great variations occur for small changes of distance. These variations are somewhat exaggerated owing to the points at this end of the curve coming

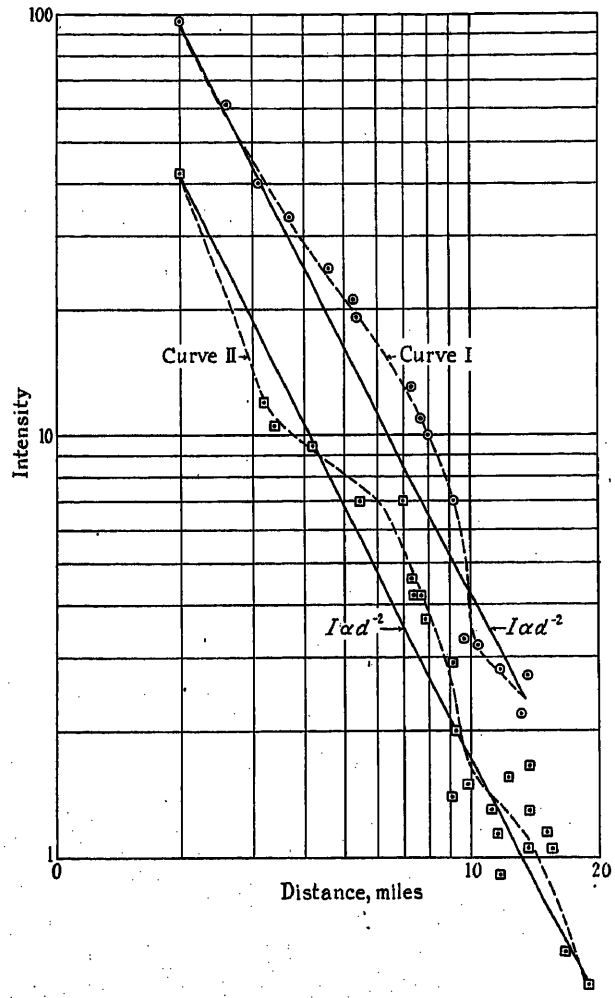


FIG. 5.—Attenuation of 5SW. (The intensity values are relative only.)

closer together for the same actual distances apart. The straight line is the curve for I against I/d^2 and it will be seen that the overall attenuation for the 18 miles approximates to that. In order to get a good average curve it therefore seemed desirable to take more observations at the shorter distance and to extend the measurements to greater distances. For this purpose the sensitivity of the apparatus was further improved and a run taken to the north-west. In this direction the country is rather more wooded and the level rises gradually to the top of the ridge over 400 ft. in altitude, at a distance of 27 miles from the transmitter. Behind the ridge the intensity decreased very rapidly,

so measurements were not taken beyond the summit. The observation points are not all accurately on the line chosen, but as near as possible to it and never more than ½ mile off it. The positions were all chosen as being good sites with no likely sources of disturbance other than the ground itself in the immediate neighbourhood of the receiver.

The results of this run are shown in curve III of Fig. 6, with the same scale as in Fig. 5, all the values observed being shown. It will be seen that the only possible average curve in this case is the straight line shown, the slope in this case being 61°. The scatter of the points gives an indication of the variations which may be expected on good sites, reckoning the accuracy of the measurements as being within 10 per cent. In some cases a reason could be found for the variations. For instance, the intensity was always greater than the average on a slope facing the transmitter and less on one facing away from it. In many cases, however, no cause was evident, so that no attempt has been made to sort out or apply corrections to the values.

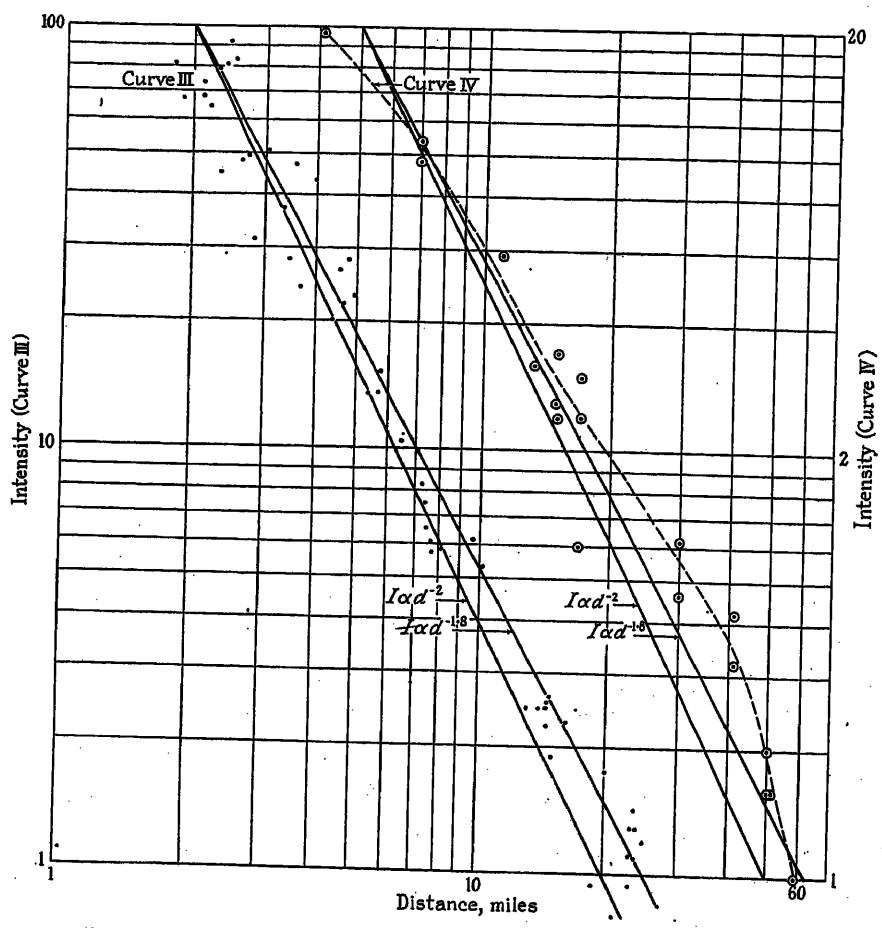


FIG. 6.—Attenuation of 5SW. (The intensity values are relative only.)

[illegible] results were considered as good as could be [illegible]nder the conditions, so it was decided to [illegible] further measurements at short distances [illegible] chosen for its uniformity, using a local sites were more difficult to find. Up to 40 miles fading was slight and little distortion was noticed, but both increased rapidly at greater distances. At 50 miles the average night intensity was 25 per cent greater than the day value. A check on this at Slough at about the same distance gave a ratio of about 2 to 1. These are, of course, isolated observations and may vary from night to night.

The results of this run are shown in curve IV of Fig. 6, the intensity scale being one-fifth that of curve III. The points are rather too few and scattered to give a satisfactory curve, as curve III shows the unreliability of isolated points for giving an average curve. The lines shown are drawn parallel to those in curve III for

One final run on 5SW was, however, taken in 1929 with the improved apparatus to see how far normal attenuation persisted and where fading and distortion due to reflected rays became troublesome. A north-easterly direction was chosen for this as, though fairly thickly wooded, the country was of a uniform level to a distance of 65 miles. Observations were taken to a distance of 58 miles, at which distance the signals were as weak as could be measured, and fading and distortion were considerable. Fewer observations were taken on this run as it was intended merely as an extension of the previous ones, and, moreover, good

reference. The last point is probably not accurate to much better than 50 per cent, owing to fading and the decreased accuracy of the measurement for such a weak signal, in addition to its being an isolated one.

These curves will be discussed more fully later in the paper.

Short-Distance Observations.

For the shorter-distance observations Dorney Common, near Windsor, was selected as a convenient and suitable site, and tests were carried out there on wavelengths of 25 and 17 m, using the portable transmitter already described. The output from this could be kept constant to within 1 per cent, so that the accuracy of the measurements is within 5 per cent. The results obtained there are shown in Fig. 7. The curves for the first two runs ($\lambda = 25$ m, curves I and II) fall practically on straight lines. To extend the available distance a line was taken in a different direction diagonally across the common, but at a distance of 1 400 ft. there was a sharp rise in level of some 5 ft. and beyond this the strength fell off with remarkable rapidity. This is shown in curve III. Owing to the weakness of the signal at the last point there is a possible error of 20 per cent.

Some observations were next taken on 17 m as it was expected that the attenuation would be greater on that wavelength than on 25 m. The results are shown in Fig. 10. It was found that while the curves had the same general slope as those for 25 m they were much more irregular. Curve I is particularly interesting. In this case, to get the maximum distance at a uniform level a line was taken passing within a few feet of the edge of a depression at the bottom of which, 4 ft. lower, was a pond in the bend of an almost dry stream. It was found that at a point 50 ft. beyond the bend, the strength of the signals was greater than at a point on the same line 50 ft. before the bend, and the improved strength appeared to be maintained beyond that point. The effect was carefully checked and confirmed. Measurements were taken at two points at corresponding distances from the transmitter but 60 ft. further from the pond, and the effect, though still present, was less marked. These points are shown with circles round them on the graph. It appears as though there is some "feeding-in" by refraction from the direction of the pond. It was hoped to investigate the effect more fully but it was not found possible to do so. Since the local surface effects seemed much more marked on this wavelength, it was abandoned in favour of 25 m.

Observations were then taken on 25 m on the upper level of the common. There the surface was very uniform and a good curve was obtained. It is shown as curve IV in Fig. 7. Again it is practically a straight line but with a different slope from the ones taken on the lower level.

Finally a series of measurements were taken on Crookham Common near Newbury where a level site, apparently very uniform, 2 miles in length was available. The results are shown in Fig. 11. For distances up to 1 500 ft. very good results were obtained, as shown in curve I, the slope of which is almost identical with that obtained for the upper level of Dorney Common over the same distance (see curve IV of Fig. 7). Beyond 1 200 ft., however, there is an appreciable departure from the straight line. At these distances there are changes in the ground-level which, though slight, may, judging by the observations on Dorney Common, be sufficient to cause departures of the order shown. With increased output from the transmitter further measurements were taken up to a distance of 12 000 ft., or over 2 miles. The results are shown in curve II. Though the points are somewhat scattered they give a reasonable average.

This completed the series of measurements. Obvious extensions of the work are suggested, and there are several points which are worthy of closer attention, but

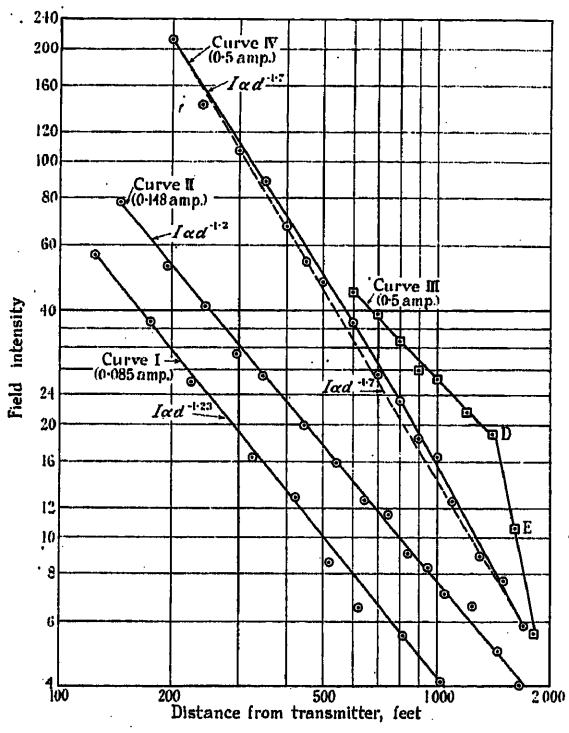


Fig. 7.—Attenuation on 25 m (Dorney Common.)
(The intensity values are relative only.)

no more was possible at the time. The curves shown, however, cover distances of from 200 ft. up to 60 miles, and much information can be gained from them in addition to that gleaned during the taking of the measurements.

Theoretical Discussion.

Various workers (e.g. Ratcliffe and Barnett,* Barfield,† and P. P. Eckersley‡) have used Sommerfeld's formulæ to produce theoretical curves to match those found experimentally and so get the value of the conductivity of the earth. An important factor in the derivation is what Sommerfeld calls the "numerical distance," the value of which is given by the expression

$$\rho = \frac{\pi}{\kappa'} \cdot \frac{x}{\lambda}$$

* See Reference (3). † *Ibid.*, (2). ‡ *Ibid.*, (4).

where x = distance from transmitter,
λ = wavelength considered,

and κ' is given by

$$\kappa' = \kappa - j2\sigma/f$$

where f = frequency of the wave,
σ = ground conductivity in electrostatic units,
and κ = dielectric constant.

If $2\sigma/f$ is greater than κ, the calculation of the theoretical curves is greatly simplified. This is certainly the case for broadcasting wavelengths, and also for wavelengths of the order of 25 m unless the ground

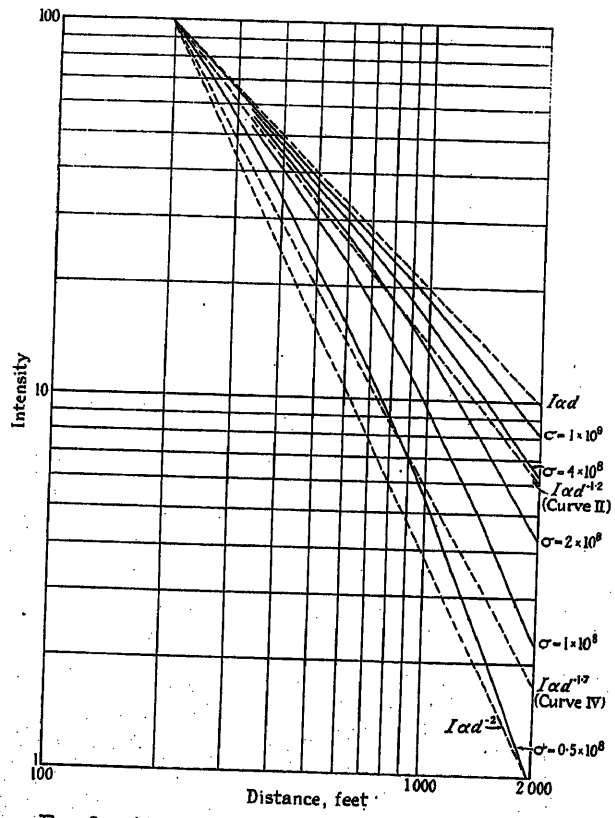


FIG. 8.—Attenuation on 25 m (Sommerfeld theory).
(The intensity values are relative only.)

conductivity is very low. Thus if $\sigma = 1 \times 10^8$ electrostatic units, a normal value for flat country, $2\sigma/f = 16{\cdot}6$ for $\lambda = 25$ m. Rolf* has published sets of curves taking full account of the dielectric constant of the earth, and the results of the present investigation have been compared with them. It is found, however, that the practical intensity/distance curves do not show the marked variations in slope predicted by Rolf. The simpler curves from the Sommerfeld formulæ are therefore used for comparison with the practical ones.

Consider first the short-distance observations on 25 m on Dorney Common shown in Fig. 7, where the intensities are plotted against distance from the transmitter in feet. The intensities are in arbitrary units but with the same units for all four sets of measurements. The transmitter current was, however, varied, the values being noted on the curves. Since the points are plotted on logarithmic paper any straight line will represent a falling-off in intensity according to a power law, the power being given by the tangent of the angle which the line makes with the horizontal. It will be seen that for curves I and II the points lie quite closely along straight lines which have practically the same slope in the two cases. These were both taken on the lower level of the common. Curve III shows the great increase in the attenuation on proceeding from the lower level at D to the higher level at E (Fig. 9). The difference in levels is about 5 ft., and the surface of the higher level appeared much drier as the grass was quite brown at the time, whereas at the foot of the slope it was green. Curve IV was taken entirely on the upper level; the much greater slope will be noticed. There is in this case a slight variation from the straight line. In Fig. 8

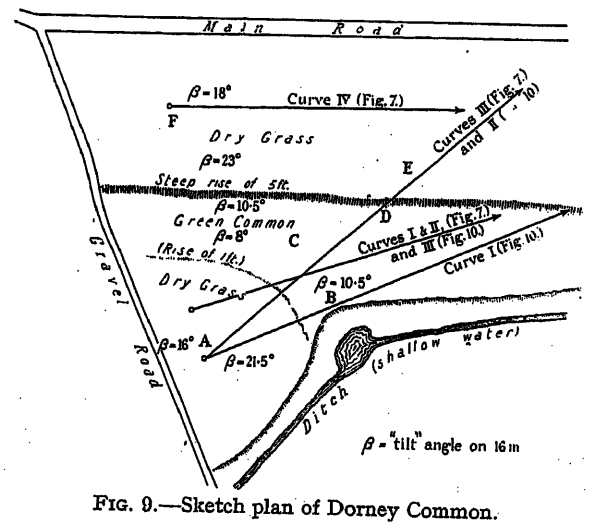


FIG. 9.—Sketch plan of Dorney Common.

are shown the Sommerfeld curves for 25 m for the distances 200 to 2 000 ft. for various values of ground conductivity (σ), with the slopes of curves II and IV of Fig. 7 for comparison. It will be seen that in each case the practical curves are much straighter than the theoretical ones, though the slopes do give possible average values for the conductivity of 3×10^8, and $0{\cdot}8 \times 10^8$, respectively.

It is interesting at this stage to consider the change in the nature of the earth surface which produces this change in conductivity, and in Fig. 9 is shown a sketch plan of the common. The measurements were taken in the summer during dry weather. Level A where the transmitter was situated was dry, with the grass mostly brown. There was a slight drop of about 1 ft. to level CD where the vegetation was much greener, and then a steep rise of 5 ft. to level FE, which looked the driest of the three. The surface soil is mainly gravel. The variations in the curve slopes with change of surface are even more marked on 18 m, as shown in the curves of Fig. 10. In curve II the first steep slope is on level A, the more gradual one from 400 to 1 200 ft. is on the CD level, while beyond 1 200 ft. on the upper level the

* See Reference (5).

intensity fell off to a value which was too weak to measure in a few hundred feet. In curve I, as already mentioned, the intensity actually increased with increase of distance near the pond at B. It is also of interest to note on this curve that the decrease in intensity between the two extreme points is less than for a $1/d$ variation.

It was found possible to check these differences in conductivity by observations on the " tilt " of the wave-fronts. The method of finding the ground conductivity by observations of the " tilt " of the electric vector in

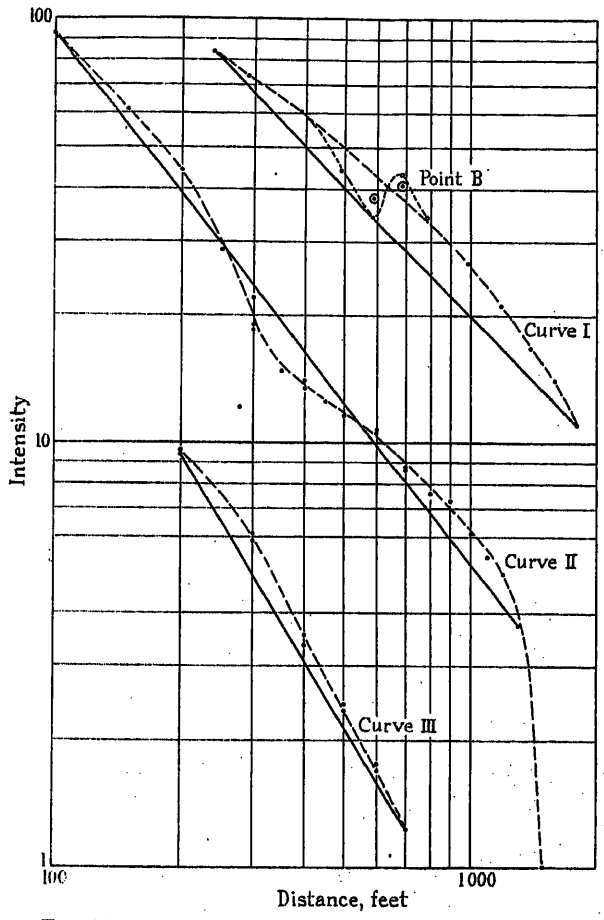


FIG. 10.—Attenuation on 17–18 m (Dorney Common). (The intensity values are relative only.)

the wave-front was used by Smith-Rose and Barfield* for broadcasting wavelengths. Mr. Barfield has since designed an apparatus for the measurement of " tilts " on shorter wavelengths, and the author is indebted to him for permission to use here the results obtained with his apparatus.

These observations were taken on 16 m on the parts of the common where the intensity measurements had been made. The observed tilts were on level FE, 18° to 23°, level CD 8° to 10½°, and level A 16° to 21°. The corresponding conductivities derived from the formula $\sigma = \frac{1}{4}\cot^2\beta . f$, where σ = conductivity in electrostatic units, β = observed angle of tilt, and f = frequency of wave, are $0{\cdot}3$ to $0{\cdot}4 \times 10^8$, $1{\cdot}5$ to $2{\cdot}5 \times 10^8$, and $0{\cdot}4$ to $0{\cdot}6 \times 10^8$ electrostatic units respectively. The relative values thus agree well with those derived from consideration of the attenuation, though the absolute values as obtained from the tilt measurements are smaller. This may be due to some extent to the shorter wavelengths used for the tilt observations, but it must be remembered also that the practical and theoretical curves did not fit well, so that there is some latitude in interpreting the conductivity from the comparison.

Consider now the observations on Crookham Common. Here the ground was almost level and of apparently uniform surface for a distance of 2 miles. Two sets of observations were taken, one for distances from 200 to 5 000 ft., and the second from 2 000 to 10 000 ft. (approximately 2 miles). The two sets of points have been plotted together in Fig. 11, and the appropriate Sommerfeld curves and slopes drawn for comparison. Here again it will be seen that the falling off of intensity can be best represented by a simple power law, the slope in this case being $-1{\cdot}7$ (the nearest Sommerfeld curve giving $\sigma = 0{\cdot}8 \times 10^8$). This is the same as for the upper level on Dorney Common. Tilts were also measured on Crookham Common at one point only, the value found for 16 m being 17°, giving a value for σ of $0{\cdot}5 \times 10^8$, which is in fair agreement with that derived from attenuation measurements. Again, it will be seen that large variations occur for apparently short changes in distance at the greater distances, though this effect is exaggerated by the logarithmic distance scale. The variations are considered to be due to surface changes in the path, this being borne out by the fact that similar variations were experienced if observations were taken at similar distances over slightly different paths.

These observations therefore all appear to indicate that the attenuation on the wavelengths under consideration depends largely on the immediate surface, the variation with changes of surface being more marked on 18 m than on 25 m.

The realization that such changes in conductivity can occur owing to the ground surface alone on what appears to be a uniform site will lead us to expect greater ones in the case of the observations at greater distances on 5SW where changes of level and the interposition of objects such as trees add their effects to that of the earth itself. The variations in the points on the curves of Fig. 5 are thus not very surprising. It is perhaps more surprising to find that the points for curve I lie so closely along the dotted curve between 1 and 10 miles. The straight lines drawn are in each case of slope -2, that is $I \propto 1/d^2$, and they will be seen to give a satisfactory average. The appropriate Sommerfeld curves for this distance approximate to this line also so they have not been drawn.

Fig. 6 shows well the " scatter " of the points for selected good sites, and suggests that the apparent regularity of the previous curves for the shorter distances may have been due to fortuitous choice of sites. The best average in the case of curve III of Fig. 6 is again a straight line, though the slope in this case is less than -2, being approximately $-1{\cdot}8$. From Som-

* See Reference (6).

merfeld's theory the curves for all values of conductivity will take up the slope -- 2 at distances of the order considered here. In this case, however, the measurements were taken on ground which rose steadily to a height of 400 ft. at the maximum distance (27 miles), so that a smaller attenuation would be expected than over level ground. Curve IV suffers from insufficiency of

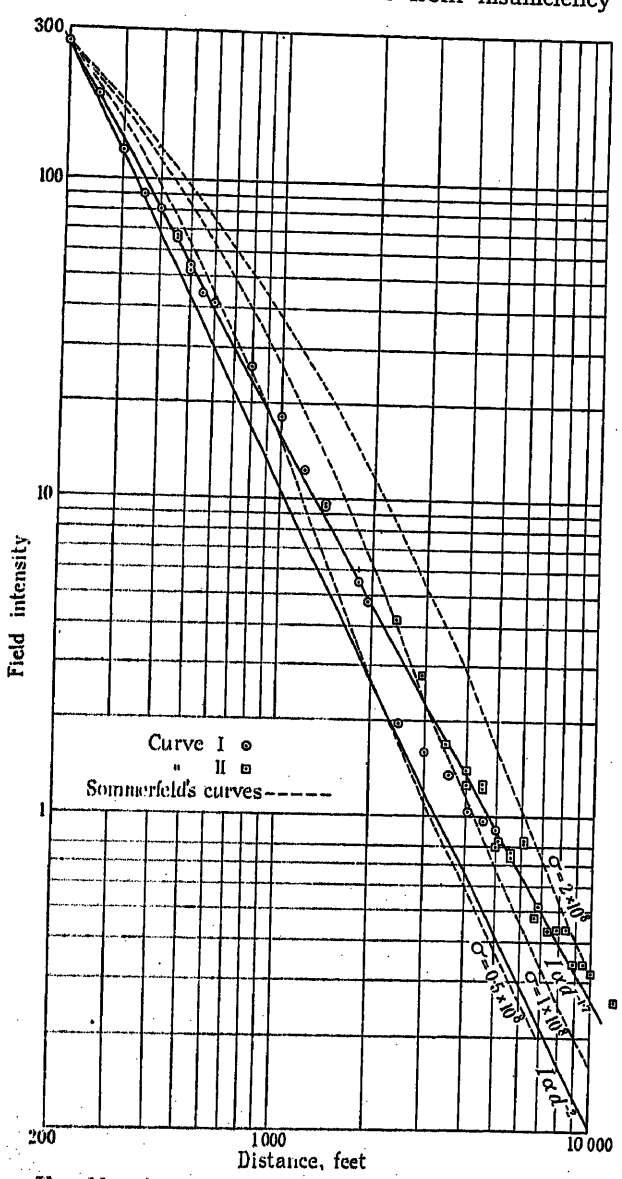


FIG. 11.—Attenuation on 25 m (Crookham Common). (The intensity values are relative only.)

points, but it shows that the same order of variation persists up to 50 miles by day. As this run was taken over level country it is probable that the curvature of the earth is also having some effect and may be in part responsible for the sudden drop which occurs between 40 and 60 miles.

Considering the complete set of observations, the following conclusions may be drawn concerning transmission on a wavelength of 25 m.

(1) For a surface of conductivity of 1×10^8 electrostatic units or less the decrease of intensity with increase of distance from the transmitter assumes, within a few hundred feet of the transmitter, an inverse-power law approximating to the inverse-square law.

(2) In all cases for conductivities ranging from $0{\cdot}5 \times 10^8$ to 1×10^8 the intensity variation is best represented by an inverse-power law for distances between 200 and 2 000 ft.

Ratcliffe and Shaw* have obtained in measurements on 30 m a bulge in the curve at 600 m from which, by comparison with the curves of Rolf, they were able to deduce a value for the dielectric constant of the earth. No such bulges were found in the present series, however, except where they could readily be traced to changes in the conductivity of the surface. It was unfortunate that the curves for the surface of higher conductivity could not be extended to a sufficiently great distance to show where the slope changed to the inverse-square law, but a suitable site of sufficient length was not available.

(3) For distances beyond 2 miles over level country, up to 60 miles—the greatest range dealt with in the experiments, great variations may be expected in the intensity at points within a few hundred feet of one another, but an inverse-square law of variation will give sufficiently good average values for practical purposes.

The deviation from the theoretical curves, and the marked changes in attenuation with change of surface, confirmed by the tilt measurements, are consistent with the supposition that the immediate surface plays a large part in the attenuation on the wavelengths under consideration, particularly if the surface conductivity is high, but where it is relatively low there is sufficient penetration to better conducting levels below the surface for these to have an appreciable effect on the (attenuation) conductivity, the resultant attenuation being a compromise between the two. As the theoretical curves are calculated for a homogeneous medium this will account for the non-coincidence between the practical and theoretical curves. Moreover, the results suggest that the surface effect is greater, and the penetration therefore less, for shorter wavelengths. This is consistent also with the observations of Smith-Rose and Barfield,† where the actual surface was found to have a relatively small effect on the "tilt" of the wavefront and, therefore, presumably on the attenuation, on broadcast wavelengths.

ACKNOWLEDGMENTS.

This investigation was carried out as part of the programme of the Radio Research Board of the Department of Scientific and Industrial Research, whom the author wishes to thank for permission to publish the results. He is also indebted to Mr. R. H. Barfield for suggestions during the course of the work.

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* See Reference (7).

† *Loc. cit.*

(2) R. H. BARFIELD: "The Attenuation of Wireless Waves Over Land," *ibid.*, 1928, vol. 66, p. 204.

(3) J. A. RATCLIFFE and M. A. F. BARNETT: "On the Attenuation of Wireless Signals in Short-distance Overland Transmission," *Proceedings of the Cambridge Philosophical Society*, 1926, vol. 23, p. 288.

(4) P. P. ECKERSLEY, T. L. ECKERSLEY, and H. L. KIRKE: "The Design of Transmitting Aerials for Broadcasting Stations," *Journal I.E.E.*, 1929, vol. 67, p. 507.

(5) B. ROLF: "Numerical Discussion of Sommerfeld's Attenuation Formula for Radio Waves," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 391.

(6) R. L. SMITH-ROSE and R. H. BARFIELD: *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 587, and 1927, vol. 116, p. 682.

(7) J. A. RATCLIFFE and W. F. B. SHAW: *Nature*, 1929, vol. 124, p. 617.

INSTITUTION NOTES.

Membership Subscriptions.

As announced at the Annual General Meeting held on the 5th May, the Council have decided to reduce the membership subscriptions to the minimum figures permissible under the Bye-laws, namely, to those in force in 1913. In the case of Companions, the class established in 1929, the reduction will be to the same rates as those of Members.

The actual reductions to be effected are relatively small, being on the average approximately 3s. per member, but in this connection it will be remembered that the higher rates fixed to meet the new conditions after the War had already been reduced, in 1924, by 10s. per member in the case of Corporate Members and 5s. in the case of Graduates. The estimated loss of revenue to the Institution due to the new reductions will be about £2 200 per annum.

Written Contributions to Discussions from Members Overseas.

Members overseas are especially invited to submit for publication in the *Journal* written contributions to the discussions on papers read before the Institution, or written communications on papers published in the *Journal* without being read. In such cases the contributor's country of residence will be indicated when the contribution is published. In this connection a number of advance copies of all papers read before the Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to contribute to the discussions.

Council's Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-Presidents, Honorary Treasurer, and Ordinary Members of Council on the 30th September, 1932:—

President. (*One Vacancy.*)

Prof. E. W. Marchant, D.Sc.

Vice-President. (*One Vacancy.*)

H. T. Young.

Honorary Treasurer. (*One Vacancy.*)

P. Rosling.

Ordinary Members of Council.

MEMBERS. (*Three Vacancies.*)

T. Carter. Prof. J. K. Catterson-Smith. H. W. H. Richards.

ASSOCIATE MEMBER. (*One Vacancy.*)

W. S. Burge.

Premiums.

The Council have made the following awards of Premiums for papers read during the session 1931–32 or accepted for publication:—

The Institution Premium (*value* £25).

J. BRUCE. "Modern Boiler Plant."

The Ayrton Premium (*value* £10).

F. LYDALL. "The Electrification of the Suburban and Certain Main-Line Sections of the Great Indian Peninsula Railway."

The Fahie Premium (value £10).

H. KINGSBURY and R. A. GOODMAN. "Methods and Equipment in Cable Telegraphy."

The John Hopkinson Premium (*value* £10).

H. W. CLOTHIER. "Metal-clad Switchgear, Automatic Protection, and Remote Control, with Particular Reference to Developments during the Last Seven Years."

The Kelvin Premium (*value* £10).

Prof. W. M. THORNTON, O.B.E., D.Sc., D.Eng., and W. G. THOMPSON, B.Sc. "The Absolute Measurement of High Electrical Pressures."

The Paris Premium (*value* £10).

E. W. DICKINSON and H. W. GRIMMITT. "The Design of a Distribution System in a Rural Area."

A Premium (*value* £10).
Dr. F. LÜSCHEN. "Modern Communication Systems."

A Premium (*value* £10).
Major E. H. E. WOODWARD, M.C., T.D., B.Sc. (Eng.), and W. A. CARNE, B.Sc. (Eng.). "An Analysis of the Costs of Electricity Supply, and its Application in Relation to Various Types of Consumers."

A Premium (*value* £5).
H. BLADES and A. C. MACQUEEN. "The Change-over of Low-Tension Distribution Systems from Direct Current to Alternating Current."

A Premium (*value* £5).
R. O. KAPP, B.Sc., and C. G. CARROTHERS, B.Eng. "Faults, and their Clearance on Large Networks."

A Premium (*value* £5).
H. PEARCE, B.Sc. (Eng.), and T. T. EVANS. "Some Notes on Oil Circuit-Breaker Design and Performance."

A Premium (*value* £5).
E. A. WATSON, O.B.E. "Coil Ignition Systems."

WIRELESS SECTION PREMIUMS.

The Duddell Premium (*value* £20).
T. L. ECKERSLEY, B.A., B.Sc. "Studies in Radio Transmission."

A Premium (*value* £10).
B. S. GOSSLING, M.A. "The Flash-Arc in High-Power Valves."

A Premium (*value* £10).
J. A. RATCLIFFE, L. G. VEDY, and A. F. WILKINS. "The Spreading of Electromagnetic Waves from a Hertzian Dipole."

METER AND INSTRUMENT SECTION PREMIUMS.

The Silvanus Thompson Premium (*value* £10).
Prof. J. T. MACGREGOR-MORRIS and H. WRIGHT, B.Sc. (Eng.). "Accuracy of Measurements made with Hot-Filament Cathode-Ray Tubes of the Gas-Focused Type."

A Premium (*value* £5).
S. H. C. MORTON. "The Metering of E.H.T. Supplies on the Secondary Side of Step-Down Transformers."

The award of Premiums for papers read before the Students' Sections will be announced later.

Swan Memorial Scholarship.

A Scholarship administered by the Institution has been founded as a national memorial to the late Sir Joseph Wilson Swan, D.Sc., F.R.S., as the result of the appeal which was made last year for subscriptions by a Committee representative of the County Borough of Sunderland (Swan's birthplace) and the Institution. The first award of the Scholarship will be made this year. The conditions of award are as follows:—

Conditions of Award.

(1) The Swan Memorial Scholarship in Electrical Engineering, which has a value of approximately £140, is tenable for one year and will be awarded annually to British subjects who fulfil the conditions set out below.

(2) Each candidate must be nominated by the professor or teacher under whom he or she is working, or has worked, and satisfy the following conditions:—

(*a*) He (or she) must have undergone a whole-time day course in electrical engineering, of at least three years, and have graduated or obtained a final certificate or diploma appertaining to such course approved by the Institution.

NOTE.—Consideration will also be given to candidates who have, for any reason, been unable to take a whole-time day course of study, but who have obtained the degree of B.Sc. with 1st or 2nd Class Honours, and who have satisfied the examiners in electrical engineering subjects.

(*b*) The candidate must be under 27 years of age on the 1st July in the year in which the award is made.

(3) Nomination forms may be obtained from the Secretary of The Institution of Electrical Engineers and must be returned so as to reach him not later than the 15th August.

(4) In considering candidates for the award, preference will be given to candidates from the Sunderland area. Such candidates must have been either—

(*a*) born in the County Borough of Sunderland, or
(*b*) resident in that Borough for a minimum of seven years, or
(*c*) educated at the Sunderland Technical College.

(5) Other things being equal, preference will also be given to candidates who, without the aid of the Scholarship, would be unable to carry out the programme of research or other post-graduate work outlined in their nomination forms.

(6) The successful candidate will be required to carry out whole-time research or post-graduate work of a nature and at an establishment approved by the Council of the Institution, and to commence such research or other post-graduate work at the beginning of the session next following the award.

(7) The Scholarship may at the discretion of the Council be awarded as a Travelling Scholarship, with a view to study abroad at some approved institution, laboratory, or works. In this event the proposed programme must be submitted to and approved by the Council of the Institution.

(8) The Scholarship is payable in equal quarterly instalments, subject in each case to the professor or responsible authority under whom the holder of the Scholarship is studying certifying that his (or her) work is satisfactory.

(9) Instalments may be withheld or forfeited in the event of an unsatisfactory report being received from the professor or responsible authority concerned.

(10) The Scholarship will be cancelled in the event of the holder relinquishing his (or her) electrical engineering research or other post-graduate work.

ELECTRICALLY DRIVEN UNDERGROUND CONVEYORS IN COAL MINES, AND THEIR ECONOMIC ADVANTAGES.

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SUMMARY.

The different kinds of electrically driven conveyors which are used underground for carrying the coal from the face to the haulage road are first described.

The different classes, viz. shaker conveyors, belt conveyors, and scraper conveyors, and, in association with these, gate-end loaders and similar apparatus, are considered in turn.

The special advantages of using conveyors and loaders in groups are discussed and the difficulties to be overcome in using such combinations are described; special stress is laid on the switching arrangements necessary to enable full advantage to be taken of such grouping.

The special points to be attended to in the design of electrical motors to be used for driving this class of apparatus are indicated.

The economic advantages of electrical conveying are then discussed; and examples of typical results obtained, showing the savings gained by the new methods, are given.

GLOSSARY OF MINING TERMS USED IN THE PAPER.

Face.—The face of standing coal about to be worked.

Long wall.—A long face, anything from 50 to 200 yards long, as distinguished from the short faces on which work is carried on in the case of room and pillar working.

Gate, gate-road.—Roads from the face along which the coal won at the face is removed to the main haulage road.

Mothergate.—If the output from a face can be concentrated into *one* gate-road this is called the "mother-gate."

Tram, tub, hutch.—Synonymous terms for the small wagons used to move the coal underground.

To brush.—To increase the height of a road by cutting up into the roof or down into the floor.

To back brush.—To repeat the brushing process; this becomes necessary when the motion of the strata closes the road either by the roof sinking or by the floor rising.

Fault.—Geological term. A break in the strata which have on different sides of the fault slipped to different levels.

Hitch.—A small fault.

Goaf, gob, waste.—That part of the workings from which the coal has already been removed.

Casting coal.—Throwing the coal along the face to the nearest gate by shovelling.

GENERAL.

The use of conveyors underground, whether at the working face or in the roadways of a colliery, is a necessary adjunct of the methods of mechanical coal-cutting now so universally adopted. It is obvious that when increasing the output from any given face an improved system of clearance must be organized, and that the use of mechanical means of removing the coal from the face is the natural complement of mechanical coal "getting."

This paper is confined to the consideration of electrically-driven underground conveyors. The only alternative to electricity which has been employed to any extent is compressed air. Many types of underground conveyor gears of recent design are so arranged that a d.c. electric motor, a 3-phase electric motor or a compressed-air turbine can be interchanged without alteration to any of the mechanical parts. The descriptions of mechanical drives are therefore applicable to any underground conveyor however driven, but since there is no question that electric power transmission is very much more efficient than compressed-air transmission, any claim as to the economic advantages of electrically driven conveyors must be somewhat modified when applied to a compressed-air drive. Compressed air should only be used where the risk of gas being present is so great that the use of electricity at the face is impossible.

British mining conditions yearly become more difficult. Most of the thick seams near the surface have been worked out, and many of those in the deeper strata have been developed until they are now long distances from the pit bottom. The greater part of our coal is won from relatively thin seams of the lower strata.

These conditions have a very direct bearing upon the type and design of conveyors to be used underground. Seams being mined at great depths, under strata which have already been disturbed by the removal of other seams—probably in a less systematic manner than present mining practice dictates—are subject to very acute roof and floor troubles. It is therefore necessary for the mining man to make use of plant which (*a*) will take up the minimum of space so that as little roof as possible will be exposed, (*b*) is of a portable nature so that it can be rapidly moved forward with the advance of the working faces, or withdrawn should conditions become unmanageable due to roof weights or other mining causes, (*c*) will continue to function satisfactorily even when movements in the roof or floor strata, or the presence of water, tend to create severely adverse conditions.

It will be seen from the foregoing that the conveying of coal underground is probably the most complex material handling problem yet tackled by the engineer, and it is hoped that the following descriptions of the progress already made will prove of interest.

Electric conveyors for underground work are usually constructed on one of the three following principles:—

(1) Shaker or jigger conveyors.
(2) Belt conveyors.
(3) Scraper conveyors.

(1) *Shaker conveyors*, as their name implies, convey the coal by giving a reciprocating motion to lengths of troughing by which the coal is made to slide in one direction along the trough.

(2) *Belt conveyors* are similar to the same class of conveyors used for surface work, and carry the coal along an endless belt.

(3) *Chain flight scraper conveyors* push or pull the coal along troughs by scraper bars or flights formed on the links of an endless chain which is pulled through the trough, partly carrying and partly scraping the coal along the bottom of the trough.

(4) *The drag bucket scraper conveyor* consists of V-shaped or rectangular bucket without top or bottom, dragged by a chain bridle attached to a steel-wire haulage rope. The bucket is dragged along the floor with the opening in the direction of delivery and gathers up the coal as it proceeds.

One or other of these types is best adapted according to the conditions under which the work has to be done. Conveyors in underground working are used to convey the coal along the face to one of the gates or roads, and to get it from this feeding point to a suitable loading station, which may be within a few feet of the working face or at the main haulage road. When the loading station is at the face, the face conveyors deliver into a gate-end loader, which simply elevates the coal into the hutches; when in the haulage road, a gate conveyor is used.

The chief difference between underground conveyors and those usually employed on the surface for industrial purposes is that the latter are usually fixed in position, and once installed and put to work remain fixed throughout their useful life. The underground conveyor has to be constantly moved as the work of cutting the coal proceeds. A face conveyor has to move daily, for as the face advances it must be moved laterally so as to keep close to the working face. The operation of moving up cannot be carried out by bodily moving the conveyor as a whole, since the props supporting the roof usually interfere with such an operation. The design of any conveyor used on the face must therefore take account of this requirement. The parts must be in reasonably short lengths easily disconnected and reconnected, and at the same time as robust as the essential quality of portability will permit. In the case of gate conveying, the change of position is not so frequent, but the length of the conveyor has to be continually increased as the face advances, and from time to time the position of the driving gear will have to be moved as new haulage roads are introduced, to prevent the length of the gates and conveyors becoming excessive.

The restrictions in construction imposed by these requirements and also by the fact that the height is in many cases very limited, call for highly specialized design, differing in many particulars from that of the ordinary industrial conveyor.

As regards the methods of use, these underground conveyors fall into two classes, viz. face conveyors working along the actual working face and delivering either into tubs if the tubs are brought up the gate, or to a gate conveyor which carries the coal to the nearest haulage road. As the conditions under which face conveyors and gate conveyors work differ considerably, different considerations enter into the design of shaker or belt conveyors, according to whether they are to be employed as face or as gate conveyors, and it is necessary to distinguish between these two different classes in the ensuing descriptions of the different types of conveyors.

Shaker Conveyors.

Coal was first conveyed underground in Germany about the beginning of this century, when sheet-steel troughs hung on chains were used on the coal face in steeply inclined seams; these troughs were swung to and fro by a boy at the top of the incline in a manner which induced the coal to slide on the pans. The next logical step was to replace the boy by an engine, and compressed air was requisitioned for this purpose. From this beginning the modern shaker conveyor was evolved.

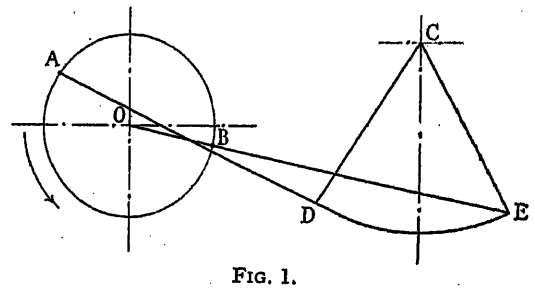


Fig. 1.

The principle of the modern shaker conveyor is to have a length of troughing resting on rollers, each pair of which runs on a specially shaped path. The driving gear is so arranged that the acceleration during the forward part of the stroke is kept down to a low value, whilst the acceleration is very much increased on the backward stroke. The coal moves forward with the trough until the acceleration reaches a definite value, depending upon the coefficient of friction between the coal and trough. At this point the friction of the trough is unable to accelerate the coal any further, and the coal therefore begins to slip. The endeavour is to keep the acceleration below this critical value for the whole of the forward stroke. On the back stroke the critical value is reached early in the stroke and the trough therefore slides back without pulling back the coal, and thus the coal travels from one end to the other of the troughing in steps.

The complete shaker conveyor consists of a driving gear embodying the electric motor and arranged to give a reciprocating motion with a very special acceleration curve to the line of troughs to which it is connected.

The principle of the gear is shown diagrammatically in Fig. 1. The crank pin is driven by the motor at a uniform rate round the centre O, and a connecting rod pivots at one end on the crank pin and at the other end on the end of a lever CE oscillating about a fixed centre C. If A and B on the crank disc represent the points at which the end E of the lever reaches the two

extreme positions of its swing, it is obvious that the distance from A to B in the direction of rotation shown by the arrow is much greater than the return distance from B to A, and since the velocity of the pin is uniform a longer time will be taken on the forward stroke from D to E than on the return stroke from E to D. The end of the lever C E will therefore move with a smaller velocity and smaller acceleration on the forward than on the return stroke. A long coupling rod of adjustable length connects the point E to the troughs, and thus imparts to them a comparatively slow forward motion and a quicker and more rapidly accelerated motion on the return stroke.

Fig. 2 shows a typical velocity curve of the horizontal component of motion of the point E. The slope of this velocity curve at any point represents the acceleration, and it can be clearly seen that the slope and therefore the acceleration is greatest in the portion A to B of the curve.

The first part of the curve represents the forward stroke of the troughing, and the ideal arrangement is to keep the acceleration small enough for the coal to be carried forward throughout the whole of the first half of

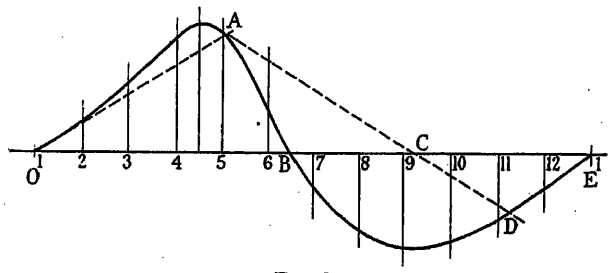


FIG. 2.

the stroke at the same velocity as the troughs. This entails that the acceleration shall at no point be greater than g multiplied by the coefficient of friction between the trough and the material to be conveyed. As soon as the acceleration becomes greater than this value, the friction between trough and coal being unable further to accelerate the coal, the latter begins to slip and goes on travelling with a uniform acceleration independent of the trough acceleration.

In Fig. 2 the thick line represents the motion of the troughs relatively to the ground and the dotted line shows the coal velocity relatively to the ground, showing that it is moving with a uniform acceleration and goes on doing so until the coal-velocity curve cuts the trough-velocity curve, when the coal will again move with the troughs and all slipping will cease. The difference between the areas OAC and CDE is proportional to the distance (relatively to the ground) which the coal will travel for one stroke of the conveyor. The amount of travel will depend on the length of stroke, on the number of strokes per minute and on the method of supporting the troughs. It is usual to provide adjustments to enable the length of stroke and the relative acceleration at various parts of the stroke to be altered. These adjustments may consist in having an adjustable crank-pin which can be moved nearer to or further from the centre of the crank disc, in adjusting the length of the lever CE and also, in some cases, in providing an additional side lever fixed to the same shaft as CE but set at an angle to it, and using the end of this side lever to connect to the troughs instead of connecting them directly to E. It is also necessary that the length of the rod connecting E to the troughs should be adjustable. In some cases springs are introduced to influence the action of the conveyor drive, but the same broad principles apply.

The troughs in the original shaker conveyors were generally suspended by chains from suitable roof timbering, but it is now usual, and has been found more effective, to provide rollers running on suitable cradles and also to fit underneath the troughs runners serving to carry them on the top of the rollers. In some cases balls have been used instead of rollers, the motion of the ball being limited by the use of a trough suitably shaped to contain it.

It is obvious that any apparatus subject to such large and sudden variations in acceleration must suffer somewhat violent shocks. It is therefore essential that all parts of the gear should be especially massive, and all the gear wheels are made as heavy as possible in the space available to act as flywheels and give the motor as much relief as possible from the shocks transmitted from the mechanism.

It is, of course, essential that the troughs should be as light as possible. They are therefore made of light sheet-steel, and one of the most difficult problems in the use of shaker conveyors is to arrange the attachment of the driving lever to the troughs, and also the attachment of each trough to the next one in such a way as to avoid damage at the point where the greatest stresses are experienced.

For this reason a special trough is generally provided for attachment to the driving gear. This is called the "driving trough" and is strongly reinforced so as to distribute the strain over a large surface of the steel.

Various arrangements of the position of the motor and driving gear with respect to the troughs are possible. Three arrangements in particular are in general use: The side drive, in which the driving gear is put down at the side of the troughing and the coupling rod is fixed to one side of the driving trough; the end drive, in which the motor and driving gear are at one end of the conveyor and connected to the end trough; and the underneath drive, in which the motor and gear are placed underneath the troughs.

In the case of the side drive or the underneath drive the gear and motor can be placed practically anywhere along the length of the conveyor. For the end drive they must necessarily be either at the top or bottom end of the troughing. In some cases also it is found expedient to keep the motor and gear away from the line of the conveyor by locating them in a gate-road. The troughing is then driven by means of a bell-crank lever actuated by the gear coupling rod. If this rod is arranged so that its length can be varied the gear can remain in position in the gate for some time whilst the face advances and the conveyor is shifted with it. Only when the coupling rod has reached its maximum length will it be necessary to shift the driving gear.

Face conveyors are not invariably used merely for moving coal along the face, but they are also at times employed to pack material in the waste for purposes of

roof control, and a side-discharge chute is then used. This is a sheet-steel chute one end of which fits into the trough and gradually carries the dirt up and round, discharging it sideways over the side of the troughing at any required point throughout the length of the conveyor.

Whilst shaker conveyors naturally give a greater output when they are conveying the coal downhill, it is quite possible to convey coal by means of shakers not only on the level but even up a gradient as great as 1 in 20, and some shakers extend to quite considerable lengths; 100 yards of troughs each 9 ft. long is not an uncommon length for a shaker conveyor, but it is obvious that the greater the length the greater the strains which will be put on the attachment to the driving trough, and also the more imperative will it be that all the connections from trough to trough shall be without play, as otherwise the cumulative effect of looseness in a large number of joints would throw most excessive stresses on the end troughs next to the engine. Various methods have been adopted for attaching the troughs one to the other, rapidity of making and breaking the joints, and reliability, being the chief considerations.

Belt Conveyors.

The belt conveyor now in general use is a more recent development for underground work, and an extraordinary feature in this connection is that in its evolution for underground use, until a few years ago, designers made no use of the results of the extensive experience and carefully compiled data which had been gathered from surface applications of this appliance. In fact, even to-day belt conveyors which embody defects that were located and eradicated in surface conveyors 20 years ago are still being installed.

The design of belt conveyors for underground work is controlled by the same requirements of portability and of restricted height already noticed in the case of the shakers.

The difficulties to be overcome in the use of belt conveyors naturally focus on providing the proper precautions to ensure as long a belt life as possible. The belting most commonly used for underground coal conveyors consists of a fabric base covered with hard rubber, and the first conveyors of this type put to work failed because of the extravagant cost due to the belt wear.

Gears for driving belt conveyors are not subject to such violent shocks as those used with shakers, and the different parts need not be of such abnormal dimensions as the class used with shakers. Nevertheless they share with all machinery used in pits the necessity of being very robust so as to stand rough usage.

The gears are frequently made so as to be entirely self-contained, the motor and the necessary switches being mounted on the side of the gear itself.

Flat Belt Conveyors.

On the coal face it has so far been found necessary to use the flat belt running between two stationary plates, one on either side of the carrying half of the belt and extending from end to end of the conveyor. This type, except in isolated cases and for very special purposes, has been—on account of its serious inherent defects—discarded by the modern designer of surface conveying plant; but under the conditions at the coal face, where ten or more men are filling on to the conveyor, at intervals of about 10 yards throughout its length, and in very restricted space, the rectangular trough formed by the stationary side plates and the belt render it a useful if mechanically crude compromise.

If it were possible to adjust once and for all, and properly set up a conveyor so that the belt would run perfectly true, these plates might be adequate for the purpose, but in a conveyor frequently shifted and where it is quite impossible to maintain the proper alignment of the belt the wear on the edges of the belt against the plates destroys it in a relatively short time.

Troughed Belt Conveyors.

Though spill-plates or side-plates are a necessary evil on the coal face, they are unnecessary in conveyors used as gate conveyors for conveying the coal from the face to the loading point. For this work a properly adapted troughed belt, as is commonly used for coal-handling on the surface, for grain handling and, in fact, for handling all raw materals in bulk, can be used.

The carrying half of the belt as it leaves the pulley at the receiving end of the conveyor is bent into a trough form by means of 3 or more rollers or idlers, and is retained in this form throughout its length by such idler groups spaced at regular intervals (3 to 5 ft.). After delivering its load the belt returns carried on flat rollers more widely spaced, as their duty is simply to carry the belt clear of the floor.

As pit roads are only used until the area to which they give access is worked out, they are far from being finished tunnels, and a belt of this description requires very adequate protection from injury due to small stones, lumps of coal, and other objectionable materials gaining access to the return belt, which would carry them along until at the end of the conveyor they were crushed under the return pulley which changes the direction of the belt, obviously seriously damaging the belt. Further, the "working" of the strata may make the floor rise in an undulating form or even twist the road slightly out of line. Provision must therefore be made adequately to protect the return belt by means of a decking. This also forms the structure on which the conveyor is built, and by which approximate alignment is maintained. "Approximate alignment" is stated advisedly as constant attention is necessary to ensure even this, but a properly designed troughed belt conveyor can safeguard its belt even when the head and tail pulleys are out of line by as much as 1 ft. 6 in. to 2 ft. in 100 yards.

There is no means of moving coal more economical of power than a well-designed belt conveyor. A consideration of the belt-conveyor designer which is second only to the conveying capacity of his plant is conservation of belt life, as the cost of the belt is roughly one-third of that of the complete conveyor. For ensuring a long life to the belt it is necessary not only that attention should be given to keeping it in correct alignment and to protecting it from accumulation of coal and dirt, but also to pay attention to the way in which the coal is loaded on to the belt. If lumps of coal, sometimes with sharp edges and corners, are dropped on to a moving belt the belt must accelerate them to its own velocity, and in

doing so will get the surface scratched and deteriorated by the sharp projections on the coal. It is therefore necessary to take care that the coal when delivered on to the belt should be already in motion in the right direction, and as nearly as possible with the same velocity as the belt. For that reason special loaders, or a short length of shaker conveyor, are frequently used so that the coal shall be delivered on to the belt at as nearly as possible the right velocity and in the direction in which the belt is running.

The designer of driving gears for underground belt conveyors is subject to the same consideration as those applying to surface conveyors. For face work, however, the use of double-drum type driving gear is imposed, because as a general rule space does not permit of a single drum of adequate diameter or of the necessary belt sag on the return belt normally allowed to secure " wrap " on the driving pulley. The second drum of the double-drum gear ensures that the belt embraces the first drum adequately, but the risk of relative movement or creep

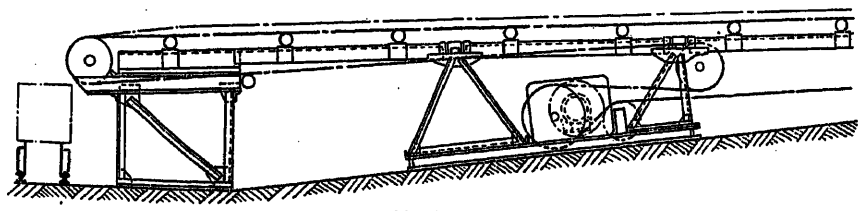
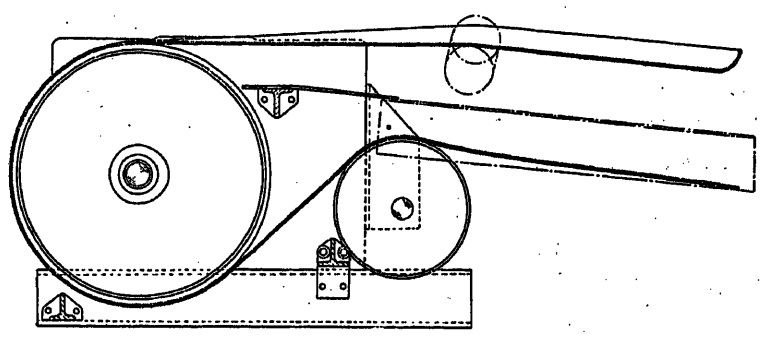


FIG. 3.—Single-drum gear.



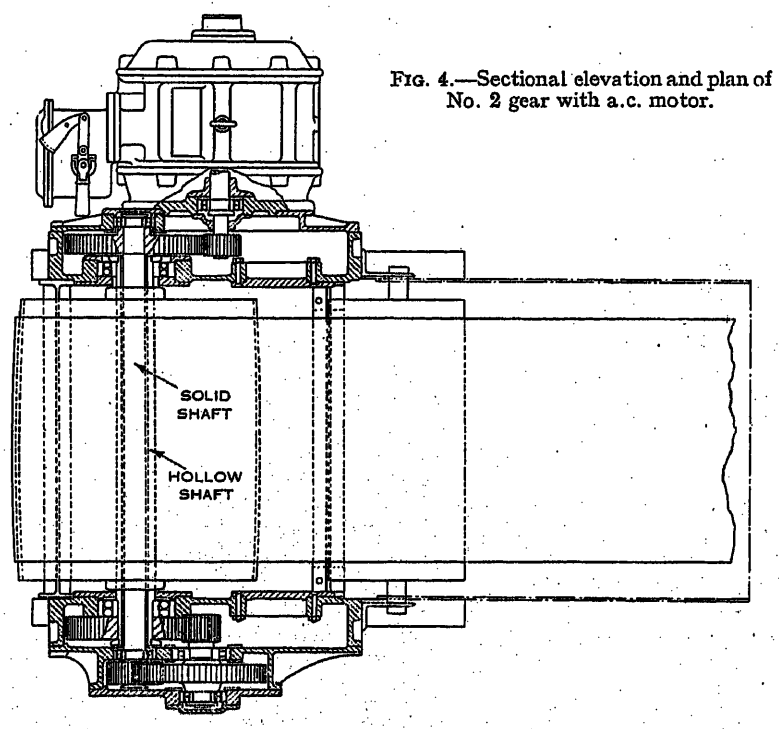


FIG. 4.—Sectional elevation and plan of No. 2 gear with a.c. motor.

between belt and driving drum is serious, and when it occurs the belt will be damaged.

The single-drum gear (Fig. 3) which is used for gate-road work can be designed in relation to the belt to be driven and the power to be transmitted. In the illustration the gear is situated under the conveyor, and as a general rule this has been found advisable because of the advantages accruing from the use of smaller head pulley, which reduces the fall of coal into the hutches, and further, it will be observed, that it permits of an adequate "sag" of belt on either side of the driving gear, thus providing a semi-automatic tensioning to the belt as it passes over the driving drum or pulley.

Fig. 4 is a sectional view of a typical belt-driving gear. It will be seen that the motor gearbox, the driving-drum and the snub pulleys are built into one compact unit, so saving space and maintaining alignment of motor and gearing, even in event of the foundation of the gear shifting—quite a likely occurrence underground.

The Chain Scraper Conveyor.

This was the first type to be applied underground in this country. In the main it has been displaced by the belt, both for face and gate conveying; nevertheless where conditions are wet or on adverse gradients in excess of 18° it still has its sphere.

The commonest form which this conveyor takes consists of a single chain having a rectangular link of malleable iron, about 9-inch pitch, and having flights or crossbars attached to every third link. This chain travels in a carrying trough round a sprocket at the driving head—which is similar to that used for the belt conveyor—thus dragging the coal along the trough to the delivery point and travelling back to the return sprocket through a return trough situated under the carrying trough. This conveyor is capable of being run out of line to quite an appreciable extent without damage, and is a sturdy, reliable appliance. Its inherent disadvantages are (*a*) it requires more power to drive than does the belt, (*b*) coal breakage is liable to occur, (*c*) it will not function satisfactorily on an undulating floor, and (*d*) it is heavier to move up.

A striking comparison was recently made in a case where a scraper and a belt conveyor were running in series in the same gate-road, both being the same length and naturally conveying the same output. The scraper was using 25 h.p. while the belt which was of the flat type between spill-plates (the most inefficient type of belt) was using 10 h.p.

The Drag Bucket Scraper.

This is simply a rectangular bucket having three sides and no bottom. The open end of the bucket faces in the direction of delivery and is hitched by a chain bridle to a flexible wire rope which passes round a sheave in the gate-road to a special 2-drum haulage gear. Another rope is hitched to the closed end of the bucket and passes round a sheave at the remote end of the coal face and round a second sheave to the second drum of the haulage gear. The closed end of the bucket consists of a hinged flap which rises and passes over the coal in its path on its inward journey, while it drops and retains the coal on its outward journey.

The haulage gear used in England generally consists of a motor of about 25 h.p. mounted between two drums to which the power is transmitted by epicyclic gearing, each gear being under control of a brake. The drum pulling the rope attached to the closed end of the bucket is usually geared to about twice the speed of its neighbour.

As applied in this country, guide rails are laid to form a path for the bucket which, travelling to and fro, would otherwise displace roof props and prove a source of danger. Into this path the coal is raked by the fillers, and at a bell signal the haulage operator draws the bucket up the face by the rope attached to the closed end of the bucket; the other rope is dragged out as it recedes from the loading point. The hinged flap of the bucket mounts the coal lying in its way, and as soon as it has passed sufficient coal the signal is given for the return journey and it is hauled out, building up its load of coal as it goes. The process is repeated until all the coal which has previously been freed by the coal-cutter is loaded off.

The limitations of this appliance are:—

(1) Only a comparatively short face can be worked under British conditions, and therefore only a relatively small output can be brought to the loading point, thus, if generally applied, imposing a large number of loading roads and diffuse working.

(2) If the strata forming the floor of the seam be soft it brings dirty coal.

(3) It requires at least twice as much power to drive it as any other conveyor.

At the same time in favourable conditions a very large output can be obtained per man-shift, but it has still to be proved whether this can compensate in every case for the added amount of "dead work" in the maintenance of additional roads and in the increased labour in collecting relatively small outputs per face unit which its use entails.

In its native country (America) the mining conditions—at least so far as underground use is concerned—are not so exacting; roof supports are not required so near the face and the seams are thicker. Cases are known where a rectangular bucket of about 2 tons' capacity is used actually to dig the coal off the face. These buckets are pulled by 150- to 200-h.p. haulages fitted with high-voltage 3-phase motors, and three men have been known to fill off 600 to 650 tons in an 8-hour shift. We, however, exploited our coal seams of this kind before machinery was invented or America was discovered, and now we must dig deeper and work harder for our reward.

Gate-End Loaders.

Gate-end loaders may be described as short lengths of conveyor on to which coal is delivered, say from a face conveyor. Their purpose is to raise the coal to a sufficient height to discharge it into a pit tub.

The original gate-end loaders were of the scraper type and consisted of a steel trough along which worked two chains carrying cross bars which scraped the coal along the bottom of the trough, but it is now quite usual to use belts, both of the troughed and flat type. Inverted steel troughing carrying the idlers acts at the same time as a protection to the return half of the belt.

Lantern slides showing these different types will be exhibited at the meeting.

For some purposes it is of advantage to be able to vary the length of the loader. With a loader used to link up a face conveyor or conveyors with a gate belt conveyor, a telescopic loader, the length of which can be altered, obviates the necessity of daily extending the main belt, and allows this belt extension to be made only at convenient intervals, say at the week-end, so that this extension does not interfere with the normal cycle of operations.

The telescopic loader has also the advantage that it feeds the coal on to the belt of the main conveyor, not from one side but directly in line with the belt and with the coal already moving in the same direction as the belt.

Different Methods of Use.

The simplest conveying arrangement is to have a single-face conveyor bringing the coal from the length of the face to a gate at one end. In some instances it is possible to lower the floor-level in the gate so that the tubs can come below the end of the conveyor, which therefore feeds direct into the tubs. Mining and economic conditions frequently render this method impracticable, and in such cases a gate-end loader may be used to receive the coal from the face conveyor and load it into the tubs. Fig. 5 illustrates this arrangement. The empty hutches are assembled on the right-hand side of the gate-road, and pass singly under the end of the gate-end loader, at the same time crossing over to the left, to be filled and taken outbye.

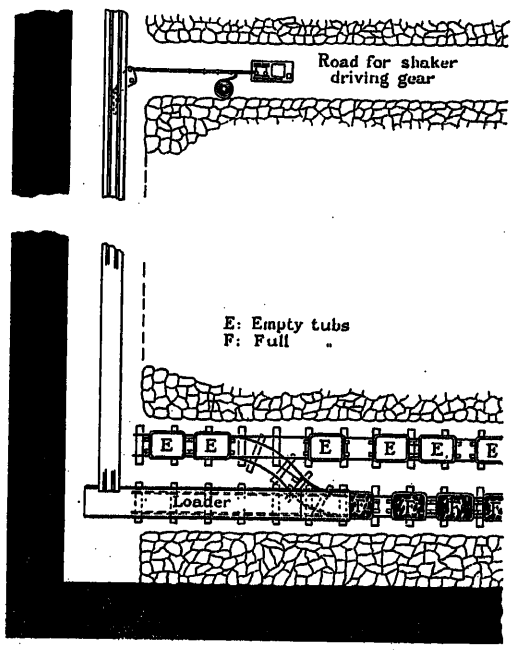


FIG. 5.—Showing joint application of face conveyor (shaker type) and gate-end loader.

Fig. 6 shows a double unit in which the face is moderately inclined, imposing the use of a shaker conveyor to the rise side of the mothergate, and a belt on the dip side. The loader is used in this case also.

Fig. 7 shows a typical example of conveying from two faces being developed to the rise, where the output is conveyed to the main haulage road. The faces in this case are shorter than usual, as the coal seam is comparatively thick, providing a large output from a relatively short face. In this case the most modern practice would be to install a regenerative troughed belt conveyor in the gate-road, which might extend to 700 yards or so before another main haulage level was provided or a new working face started from the same level further along the main haulage road.

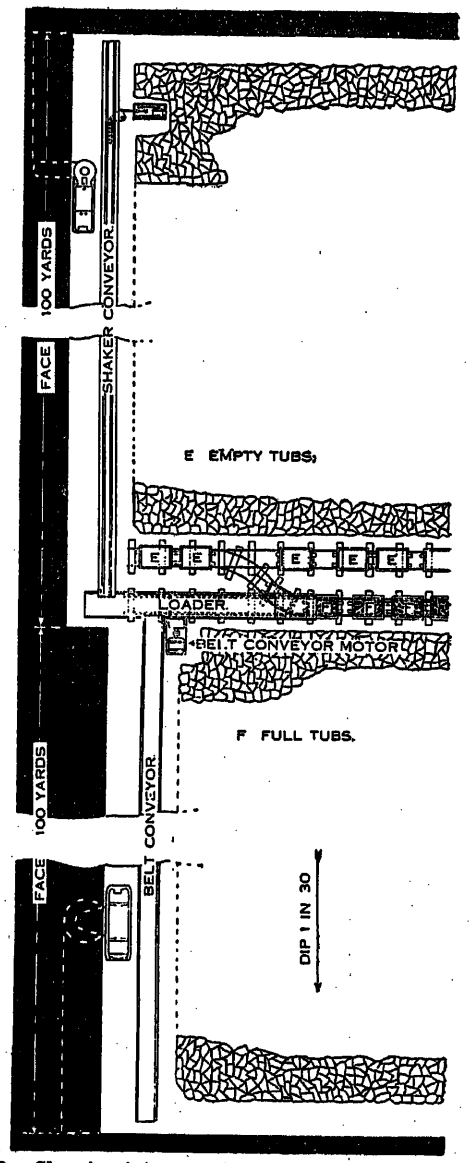


FIG. 6.—Showing joint application of face conveyors and gate-end loaders.

The four foregoing examples serve to illustrate (*a*) a single unit, (*b*) a single unit with gate-end loader, (*c*) a double unit using one belt, one shaker and a gate-end loader, and (*d*) a double unit using two shakers and a gate-belt conveyor. There are many variants of these typical arrangements. For example, where long faces are worked for the purpose of concentrating large outputs to one point it is now common to run two or more

face conveyors in series, delivering on to a gate-belt conveyor, or a loader modified to allow of standage for a complete train of hutches, so that no delay in clearance of the output will take place.

One case requiring special notice is that of a belt conveyor conveying downhill at such a steep angle that the load takes charge and accelerates the belt independently of the motor. In such a case either a 3-phase or a shunt-wound d.c. motor will, when run over speed, automatically act as a brake and put power back into the line, but any failure of supply will, by taking the excitation off the a.c. motor, allow the conveyor to run away, and it is therefore essential to fit an automatic brake which will be applied by a failure of the supply. In the case of a d.c. motor the failure of supply does not take off the excitation, but if the circuit is interrupted, e.g. by a fuse blowing, the speed will increase with no check from the motor, and as this is still excited it is not possible to apply a simple solenoid-controlled brake. If the solenoid is on the motor side of the blown fuse the motor keeps it excited, while if on the other side of the break it is still excited from the main supply; it is therefore necessary to have some arrangement of centrifugal governor to control the mechanical brake, or to fit an over-voltage relay which will trip the solenoid circuit when the motor speed becomes excessive.

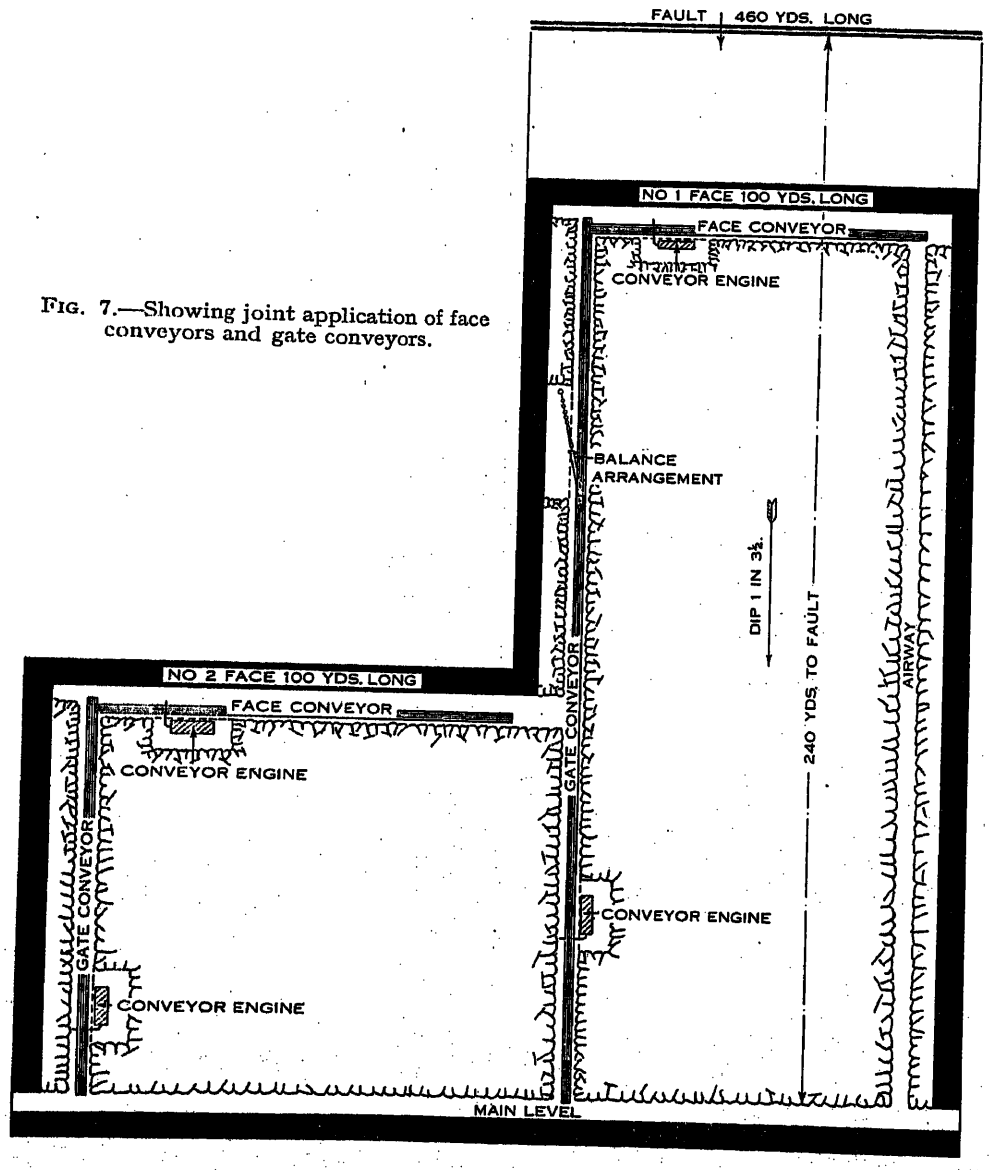


FIG. 7.—Showing joint application of face conveyors and gate conveyors.

When combinations of several conveyors feeding into one another, or combinations of conveyors and gate-end loaders, are used, it is obviously necessary that means should be taken to prevent an undue accumulation of coal at any intermediate point. For instance, if two face conveyors are feeding on to one loader, and the latter has to be temporarily stopped, either through want of tubs to load into or from any other accidental cause, the face conveyors must also be stopped as otherwise the loader will be buried in coal which it is

unable to get rid of. In such cases it is therefore quite common practice to fit distant-control switchgear so that the man at the loader is able to start and stop at will the whole of the machinery, and several systems of such control have been devised to meet special cases.

Switchgear.

The switchgear actually used varies in different cases from simple air-break drum-type switches with a fuse in each line to automatic switches embodying electrical interlocks and a number of safety devices, but all are contained in flameproof cases and are adapted to be mounted either on the side of the gate-end loader or on skids so as to be readily movable with the rest of the gear. Let us take as an example one of the simple cases where two conveyors are feeding one gate-end loader. Three switches of the ordinary air-break type are mounted side by side on the frame of the loader. The main supply is brought in to the three switches by means of a gland connected on to a trailing cable, and the two switches controlling the conveyors also have plugs fitted to trailing cables, taking the output to each conveyor motor. The current to the loader motor can be taken through an ordinary armoured cable, since the motor and switch are both mounted on the loader frame and are never moved relatively to one another.

Mechanical interlocks are provided to ensure that the plugs cannot be withdrawn when the corresponding switch is "on," nor can the switch be put "on" when its plug is not in position. The operator at the loader has thus the three units of the plant under his control and can start and stop them as required.

In the case of a number of conveyors feeding into one another in series, they must, of course, be started in the proper sequence. One of the conveyors must not begin feeding into another which has not yet been started; it is therefore necessary in such cases to provide a mechanical interlock between the switches so that they can only be operated in the correct order.

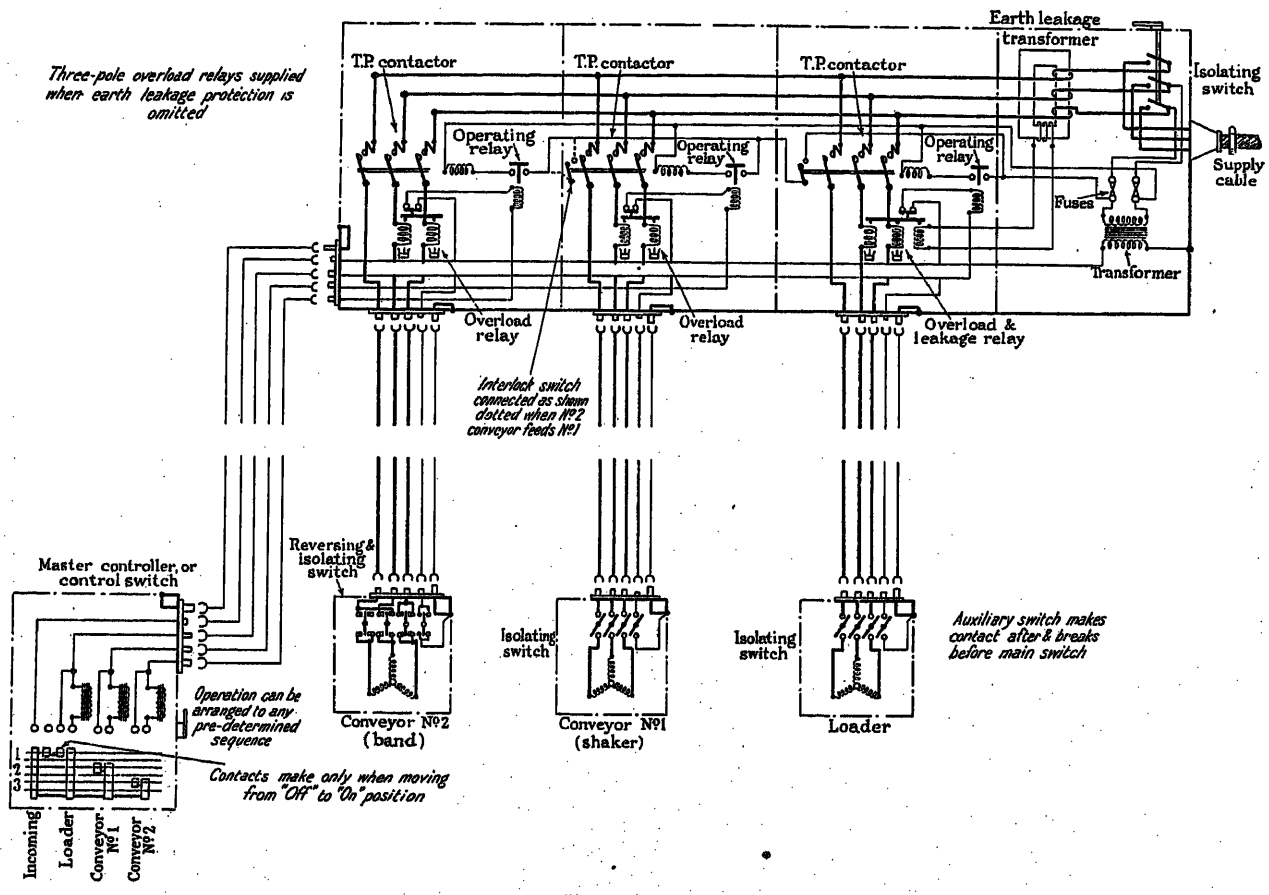


Fig. 8.

A more elaborate switching arrangement is obtained by substituting contactor switches with overload and no-volt trips for the simple drum-type switch with fuses. In order, however, to ensure the maximum possible amount of safety, combined with automatic control of the sequence of starting the different units, it is necessary to install some system of remote control by using a combination of contactor switches with a master controller, giving direct control of all the units.

The simplest of these systems, however, requires a trailing cable with five cores, as a pilot wire is required in addition to the three conductors and the earth wire in the ordinary trailing cable.

Fig. 8 shows diagrammatically the connections for one such system of remote control as applied to three units, say a loader fed by two different conveyors. On tracing out the connections it will be seen that as soon as the isolating switch in the gate-end box is closed the transformer is made live through the two fuses shown. The secondary circuit of this transformer passes along the pilot wire to the master controller, the contacts of which close the pilot circuit (1) to the loader switch, (2) to conveyor No. 1, and (3) to conveyor No. 2. In each case the pilot circuit is closed through the coil of the operating relay, which allows the main coil to take current and closes the contactors.

As the loader contactors close, a small interlock switch which is included in the circuit of the main coil working the contactors of conveyor No. 1 also closes. This switch thus ensures that if for any reason the loader contactors have failed to close it is not possible to start conveyor No. 1. The same connections and series of operations are repeated on positions 2 and 3 of the master controller, ensuring that the loader and conveyors (1) and (2) start in the proper order. Before the master controller reaches position " 1 " it closes two contacts which complete the pilot circuit and excite the coil of the operating relay so as to close the contacts. If for any reason (say the loader being buried in coal) the motor fails to start, the overload coils will open the contactors, but immediately the current is off and the overload relay closes, the operating relay will again operate and put in the contactors, and these will therefore be kept chattering off and on until the obstruction is removed and the loader motor allowed to start. To obviate this the completion of the first step of the master controller introduces into the pilot circuit an inductance so proportioned that it allows sufficient current to pass to hold down the operating relay if this is closed, but insufficient to close it if it is open. This prevents the alternate closing and opening of the contactors if the motor fails to start, but it is obviously necessary that it should not be possible for the master controller to remain in the position where the inductance is not in circuit: this position is therefore not reckoned as one of the steps of the controller, and the star wheel is so arranged that the handle cannot be left on that position.

As a safeguard against earth leakage a transformer can be supplied which, on any out-of-balance occurring in the three mains, operates a coil working the overload relay of the loader motor contactor.

The following safeguards are therefore provided. The contactors of any motor will open (1) if the pilot circuit is broken, the operating relay being thereby opened, and (2) if the contactors of any motor which should precede it in the predetermined sequence come out because the interlock switch comes out with the contactors and breaks the circuit to the following main coils.

The pilot circuit is broken (1) if there is any break in the earth connection, (2) if any plug is pulled out, (3) if the overload or leakage relay operates, (4) by the action of the master controller.

The contacts of all the plugs are so arranged that the pilot wire breaks before and the earth wire breaks after the main contacts. If, therefore, it is attempted to pull out a plug when the circuits are alive, the pilot-wire circuit will be broken and the contactors come out before the main circuit breaks at the plug contacts. On the other hand, the earth wire breaks last so that the apparatus remains earthed until after all the other connections have been broken.

An auxiliary switch working in connection with each of the motor-isolating switches is provided in the pilot circuit; it makes contact after and breaks contact before the main switch, and thus ensures that both make and break take place on the contactors and not on the isolating switch.

It will be seen on consideration of the above points that a system of remote control can be devised which is practically fool-proof, and that it is not possible to attain the same amount of safety except by adopting remote control. In particular there is one feature in any system working with hand-controlled switches and ordinary trailing cables which has been the cause of some fatal accidents. On such a system the plug at the conveyor-motor end of the trailing cable can be interlocked with the motor switch so that it cannot be pulled out when that switch is on, but there is nothing to prevent its being pulled out if the gate-end switch has been left on, and the plug therefore remains alive after it has been taken out and thus becomes a source of danger. It is obviously impossible to make sure that this does not happen except by some system of remote control which will automatically fetch out the gate-end switch when the plug at the far end of the trailing cable is pulled out, and this is one important point in favour of the general adoption of automatic control.

There is one point to be noticed in the construction of the plugs themselves. If for any reason any of the pins make bad contact in the tubes, sparking may take place even when the plug and socket are properly assembled. It is therefore necessary that the chamber containing the pins and tubes should, when the plug is in position, form a flameproof enclosure complying with B.S.S. No. 229. Modern plugs are made to comply with B.S.S. No. 279, which ensures compliance with this flameproof requirement and at the same time fixes certain of the dimensions so as to secure interchangeability.

The British Standards Institution have a specification of a 100-ampere plug suitably designed to meet these requirements, and, while others exist the use of which is permitted, for the purposes of this paper the British Standard plug may be taken as typical.

Designed primarily for use on a 3-phase alternating-current circuit, it is also used on d.c. circuits, the only difference being that one pin contact is omitted.

The plug has four sockets grouped symmetrically in a cylindrical moulded insulator, which in turn is encased in a cast bronze housing to which the earth connection is made. The four contacts provide for the 3-phase leads and for a pilot core when this is required. The socket to receive the plug is provided with four corresponding pins also carried in moulded insulation and encased in a bronze housing. The mouth of this housing contains a ring the internal diameter of which is a fit for the external diameter of the plug. The ring is cut axially to ensure a spring contact on the plug casing, and is of such a depth that the plug is entered $1\frac{1}{4}$ in. into its bore before contact is formed with the pins in the socket.

In this way it will be seen that in entering the plug into the socket two safeguards are provided: (1) The earth circuit is completed through the plug housing and socket, before the live terminals marry, and (2) before the live terminals marry a flameproof enclosure is formed in the contact chamber, so that if the machine be earthed or a fault be present which will cause arcing no danger of external explosion exists. To safeguard against an internal explosion as described in (2) blowing out the plug, the plug is so arranged that it cannot be entered into the socket so far as the contacts before a controlling screw is engaged in a slot provided on the side of the plug body. When a switch interlock is required, as in cases when remote control is not used, a recess is formed in the control screw body into which the interlock plunger drops when the plug is fully engaged.

Usual precautions are, of course, taken against the access of damp to these plugs. In the majority of cases they are used in conjunction with the 4- or 5-core type of cab-tyre flexible cable, i.e. 3 live cores and an earth core, or, alternatively, 3 live cores, a pilot core, and an earth core.

It will be seen that all live contacts are adequately masked, and that the construction is simple and robust. A number of similar plugs are also used, but generally these are engaged by the large circular-nut principle, which involves heavier and more cumbrous construction.

Electric Motors.

The design of electric motors for use at the coal face is restricted in various directions. Firstly, the dimensions of the motor must be kept down to such limits as will allow it to go into and to be fairly easily handled in the seam where it has to work. The height is, of course, the more important dimension and is strictly controlled by the height of the seam. Secondly, it must in most cases be flameproof. Thirdly, it must if possible stand without breaking down whatever treatment it may be subjected to in the hands of an operator whose knowledge of electrical apparatus is strictly limited and whose sole object is to get more and more coal, with in some cases, it is feared, the minimum consideration for the machinery which helps him.

From the manufacturer's point of view the motors of the gears must be standardized and capable of being made in quantities. It is accordingly the usual practice to make flameproof all motors for underground conveying in collieries, the number of collieries in which this precaution is not necessary being relatively small.

The heights of the motors and gears are restricted, and for the thinner seams an overall measurement of about 13 in. to 16 in. is common, whilst for thicker seams the restriction of height is, of course, less important.

The length and breadth of the machines have also to be kept within the smallest possible limits in order that the minimum of unsupported roof may be exposed, and that the machine may be as light and as easily handled as possible, thus facilitating the frequent changes of position of the conveyor.

In present-day practice the supply to the colliery for which the motor must be designed is usually 3-phase. Unfortunately the periodicities and voltages differ considerably from district to district, and there are still a considerable, although diminishing, number of places where direct current is still in use.

The motor used to drive conveyors on a 3-phase supply is almost invariably a squirrel-cage induction motor, and it is the common practice to switch the motor straight on to the mains without any special starting device. In the early days of motors being used at the coal face for coal-cutting and conveying, the more orthodox method of putting in wound rotors with slip-rings was generally adopted. It was found from experience that the greater simplicity of the method of switching direct on to the mains appealed to the colliery proprietors, and that when the current was taken from a public supply or from a private plant of adequate size no ill-effects arose from this method of starting.

In many instances of motors, originally sent out with wound rotors and slip-rings, coming in for repairs it was found that, the starting resistance or switch having given trouble, the colliery electricians instead of having any repairs carried out had merely short-circuited the slip-rings, and thus made the machine into the equivalent of a squirrel-cage rotor. It is obvious that in the case of motors receiving the treatment usually meted out to underground motors it is of the utmost importance that simplicity should be the guiding principle of design, and the advantages of the squirrel-cage rotor without any moving contacts are obvious. Even in those cases where auto-transformer startors were provided they were an additional complication and source of possible trouble, and when any trouble arose with them it was found that the usual practice of the colliery electrician was simply to remove the auto-transformer and only use the switch to put the motor straight on to the mains. This method was therefore almost universally adopted except for motors of the very largest size, and is now practically standardized.

Further difficulties to be faced by the designer are due to the fact that the load of all coal-face machinery is in many cases very intermittent, and worst of all that the demand to be made on the motor will vary largely in different places and under different conditions, and can seldom be even approximately estimated beforehand.

The problem for the designer, instead of being, as is usually the case, to make a motor to give a definite horse-power at a definite speed and to make it as small and as cheap as possible, is inverted in this case, and may be stated thus: Given the maximum dimension which may be used, put into that space the most powerful motor that can be obtained. It is obvious that under those conditions a motor cannot be designed to any of the standard specifications, and the proper attitude for the manufacturer (although it is sometimes difficult to persuade the customer to share this view) is that he is not selling a motor of any given horse-power but that he is selling complete a gear, whether for conveyor, coal-cutter or whatever it may be, embodying that motor which his experience has led him to choose as being the most suitable for that particular job.

The 3-phase motors for conveyor gears are designed to give a stalling torque much in excess of what would be usual in commercial motors, so as to get over the frequent temporary overloads thrown on them, and are

frequently run by the operators at such overloads as to cause very considerable temperature-rise. In the case of 3-phase motors this temperature-rise is the only symptom of the motor being considerably overloaded, but it is possible with improved methods of insulation with heat-resisting material to make motors which will stand high overloads and high temperature-rise without damage to the insulation. In the case of d.c. motors, however, the conditions are different. In addition to overheating, excessive overload also causes sparking at the commutator, and this cannot be avoided.

When a 3-phase motor has been tested at a certain load and is put into the hands of the colliery operators it can be definitely stated that it is capable of a certain average load, and that if it is found to be overheating at the end of a shift it is because it has been asked to do too much.

When a d.c. motor has been tested with the commutator in the best possible condition and with the brushes adjusted by skilled testers, there is no guarantee whatever that in actual working conditions it can repeat the same load without sparking. The condition of the commutator may have been allowed to get much worse, the brushes may be badly out of adjustment, and if the conditions in a thin seam are considered it will be seen that no very great blame attaches to the operator if these adjustments are not always kept at their best. Further, on account of the indefinite and intermittent load only a hit-and-miss type of adjustment is possible while the machine is actually at work. The fact that everything has to be kept down in size and at the same time that the whole of the motor casing must be flameproof makes it exceedingly difficult to make the commutator really accessible, and when manufacturers put forward claims of accessibility for their machines it has to be remembered that the term is relative. Whilst accessibility may be quite rightly claimed for some machine because it is better than in competing machines, nevertheless in a commercial motor where all the above restrictions were absent the commutator would be considered very inaccessible indeed. If, added to this, it is considered that the work of adjustment must be carried out at the face with perhaps only 18 in. between floor and roof, and also that whilst actually at work the machine must be totally shut up so that what sparking occurs can only be seen through small peep-holes, it will be realized that it is next to impossible that the motor should be working under its best conditions. It follows from this that the problem of driving coal-face machinery electrically is easier on a 3-phase than on a d.c. supply.

Although, as can easily be seen from the above considerations, it is not possible to make motors for conveyor work which will comply with the requirements of standard specifications so far as heating and electrical qualities are concerned, there is no difficulty in complying with all the requirements for flameproof enclosure contained in the British Standard Specifications for flameproof enclosure (No. 229) and for motors for use in mines (No. 270). Such flameproof enclosure must of necessity be provided whenever the motor is to be used in a fiery mine, and apart from any danger of explosion the shell must be strong enough to give the working parts reasonable protection against mechanical damage from falls of roof and similar accidents.

Economic Advantages.

The economic advantages of mechanical conveying fall under two different heads. There is a definite saving in the number of men required to clear a face when mechanical means of conveying the coal are provided, and, as will be seen from some of the actual examples given below, this saving more than compensates for the depreciation and interest and running costs of the conveyor; but very much more important than this is the saving realized when mechanical conveying is combined with mechanical coal-cutting, due to the totally different organization of the intensive working imposed by these mechanical aids.

The concentration of the output from a much smaller number of faces is a matter of great importance. The output from very much longer faces can be brought to one "mother gate-road" when worked mechanically than is possible in the case of hand work, and the savings effected by this concentration are extremely important. Not only does it mean a very greatly decreased cost on keeping open roads which can now be much fewer in number, but there is also a definite advantage, and in places where the roof is tender a very considerable saving is frequently realized from the rapid and perfectly regular advance of the face which effects a reduction in the cost of timbering, as much of the timber can be extracted and used again as the face advances.

Instead of working more or less at haphazard the transport of coal can now be definitely organized, much in the same way as the transport of manufactured articles can be organized in a mass-production factory. The same cycle of operations is carried out day by day and every man knows exactly what he has to do. In a properly organized mine the operations are exactly repeated from day to day and a regular advance of the working units of face may be relied upon. In the place of ten or more gate-roads to a working face, to which the coal must be cast and at which the tubs must be filled, then to be pushed by hand to the centre or mother-gate, in which a subsidiary haulage is installed to take the tubs to the main haulage, the centre or mother-gate suffices for loading, and the labour of casting the coal back to the gate-roads and pushing the tubs to the haulage, attaching them thereto and detaching them, again to attach them to the main haulage, can now be eliminated.

The labour entailed in turning over coal which has been cut by a coal-cutter from the face on to a face conveyor is naturally less arduous than that expended in the casting and tub filling as described above; and on a properly organized conveyor face the output per filler is, as a result, at least doubled. Further savings are, in favourable circumstances, effected by the reduction in the number of gate-roads required to the face, though in some cases it is still necessary to extend the work applied to these roads, to gain material to build pack walls to control the roof under the changed conditions.

Offset against these savings is the cost of moving up

the conveyors to follow the face advance, interest, depreciation, maintenance, and power costs on the plant. The latter charge, in a few isolated cases where gate-road troughed belt conveyors are used, has been considerably modified; when the workings are going up an appreciable incline, regenerative conveyors are used, and power proportionate to the output is put back into the line. A case of this kind where the entire output of a colliery, amounting to 3 000 tons per day, is being brought down the hillside from the mine, shows the remarkable regenerative capacity of 50 h.p., which, taken over a year's working, should approximate to a saving equal to the total depreciation and maintenance of the entire conveyor plant.

The old method of longwall working is illustrated in Fig. 9. A longwall face was opened out; its length was indiscriminate, but generally speaking it had a mothergate into every 100 yards of face, running obliquely to the mothergate were cross-cuts, and at intervals of about 45 ft. were gate-roads joining it to the face. These cross-cuts were driven through the waste at intervals so as to limit the length of the gate-roads.

When the coal was hand-won, the face was often allowed to develop according to the capacity of the

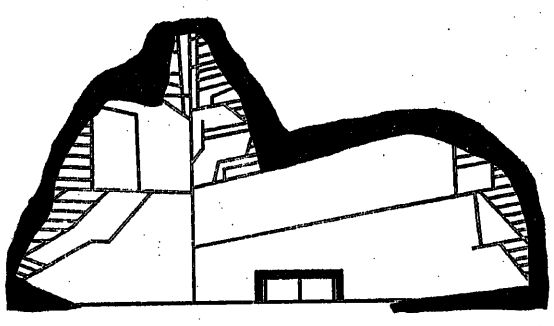


FIG. 9.

individual hewer; he hewed his coal and cast it to the nearest gate-road (i.e. a maximum of about 25 or 30 ft.), which would sometimes under difficult conditions entail three casts. At the gate-road a boy was employed whose duty it was to fill the hutches and push them down the gate-road to the main haulage. Each gate-road had to have a rail track laid in it, and had to be maintained at adequate height to allow the loaded trams to pass; this entailed brushing, and again in most cases back brushing, i.e. cutting up into the roof or cutting down into the floor. The gate-roads in most cases had to be propped by timber. At the mothergate the hutches were marshalled by pony boys, who gathered them from the gate-roads and pulled small trains to the haulage. If the gate-roads were on an up gradient the hutches had to be pulled out to the mothergate by ponies also.

The average output of a hewer in a 3-ft. seam undercutting by hand and drilling and firing his own shotholes was generally in the neighbourhood of 6 tons per shift, say 0·84 ton per yard of face, i.e. one hewer could deal with about 7 yards of face per shift. A comparison on these assumptions of the working of a face 100 yards long by the old hand-working methods as compared with mechanical coal-cutting and conveyors is given below:—

	Man-shifts
Hewers (getting the coal and casting to gate)	14
Drawers (filling the tubs and pushing them to mothergate)	14
Train marshal (getting tubs into small trains)	1
Pony drivers (pulling trains to main haulage)	3
Haulage attendant	1
Fireman	1
Brushers (road maintenance)	7
	41

These figures are for 84 tons of coal, making the weight per man-shift 2·05 tons.

Comparing the above hand-worked face with a similar face 100 yards long worked with a coal-cutter and conveyor, the seam being 3 ft. wide and the coal-cutter undercutting 4 ft. 6 in., the output will be about 1·4 tons per yard of face (the coal-cutter undercutting deeper than is possible by hand). When filling cut coal on to conveyors a man can comfortably load 15 tons in an 8-hour shift, and the number of men required will be:—

	Man-shifts
Coal-cutter attendants, Hole driller, Shot firer } getting the coal	2, 1, 1
Fillers (shovelling on to conveyor)	10
Conveyor attendant	1
Tub loaders	2
Train marshal	1
Conveyor shifters	3
Fireman	1
Brushers	5
	29

The weight of coal in this case is 140 tons, making the weight per man-shift 4·83 tons.

These figures are typical of the savings that can be made by changing from hand-working to mechanical working, and indicate the economies which can be realized with the best conveyor practice; in favourable cases the above figures can be improved upon. It has not been found possible to give actual figures of any given case of change-over; in most collieries the process of changing is gradual and extends sometimes over a very considerable period of time, and colliery records are not usually kept in such a way as to make the required figures readily accessible, even were the management willing to disclose them.

The economies additional to those derived from the increased output per man employed depend on obtaining a greatly increased output delivered to the main haulage at one point. It can readily be seen from the above examples that the more fillers can be employed as one unit the better will be the ratio of fillers to the day workers, i.e. to the oncost men.

In the comparison given above it will be seen that the elimination of all the gate-roads, the conveying being done along the mothergate only, has decreased the number of brushers required. In addition to these,

however, the concentration of output may result in having to keep open a much shorter total length of main roads; it may result in getting the whole output required from one district instead of two or three, with a very considerable saving on maintenance of roads.

The authors encountered an extreme case not long ago where an old colliery was turned over from hand-winning to machine-cut and machine-conveyed coal; before the introduction of machinery the working faces

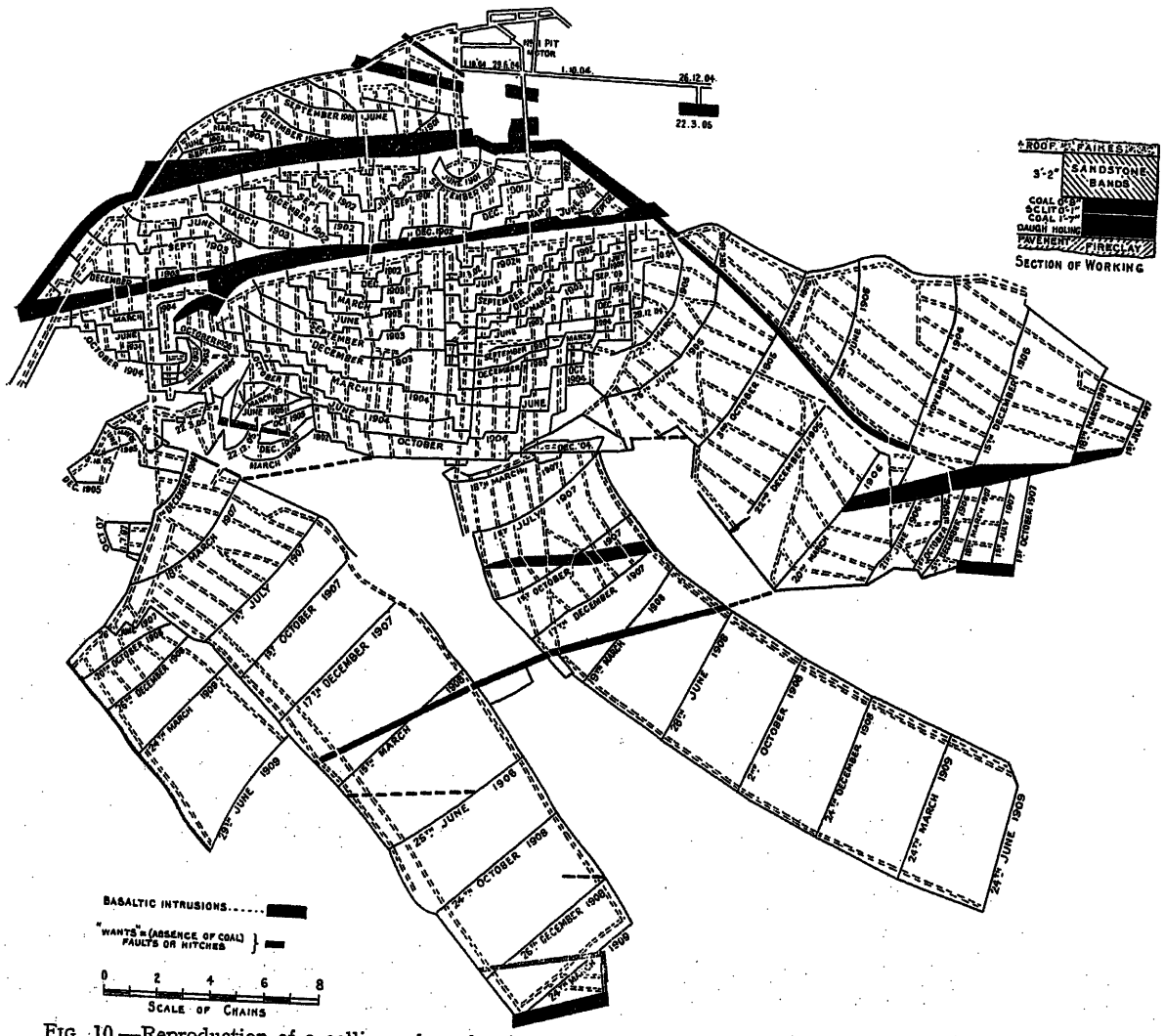


FIG. 10.—Reproduction of a colliery plan, showing the evolution of coal-cutter and conveyor sections from hand workings in a seam troubled with faults.

totalled 2 miles in length and were scattered over several districts. Three 100-yard faces equipped with conveyor units were started, and the rest of the pit was laid idle. Within three weeks the output of the colliery was normal and the output per man employed above and below more than doubled. Before the introduction of machinery more men were actually employed on road maintenance and transport than on hewing coal.

A practical illustration of the concentrative effect of the application of coal-cutters and conveyors is shown in Fig. 10, which is an actual colliery plan; the quarterly survey lines show clearly the rate of advance of the working faces. Where the survey lines appear close together the coal was got by hand; the intermediate stage where the lines become straighter and wider apart, with a number of roadways (shown by dotted lines) to the face, show the start of coal-cutting. The widely-spread surveys with only two roads, one at each end of the face, illustrate vividly the speeding-up resulting from the application of a single-unit conveying system. Fig. 11 is a drawing to a larger scale of two sections of the same plan, showing the hand-won and machine-won faces.

With the introduction of concentrated mining, important research on road-making and maintenance has been started and the science of mining has naturally developed along lines which will assist the reliable function of the machinery and the certainty of obtaining the output regularly and without interruption from accidents to the main roads. In many cases where roadways were maintained only at the cost of repeated

back-brushing (i.e. heightening) and re-timbering, it is now possible so to construct the roadway in the first instance that it will remain in reasonable working condition until the area is worked out.

Taking all the savings which can be effected by changing-over from hand-got to machine-got and machine-conveyed coal, it may be said that savings as great as 50 per cent in the cost of the coal at the pithead have been realized in favourable cases, whilst a saving of 25 per cent is not uncommon.

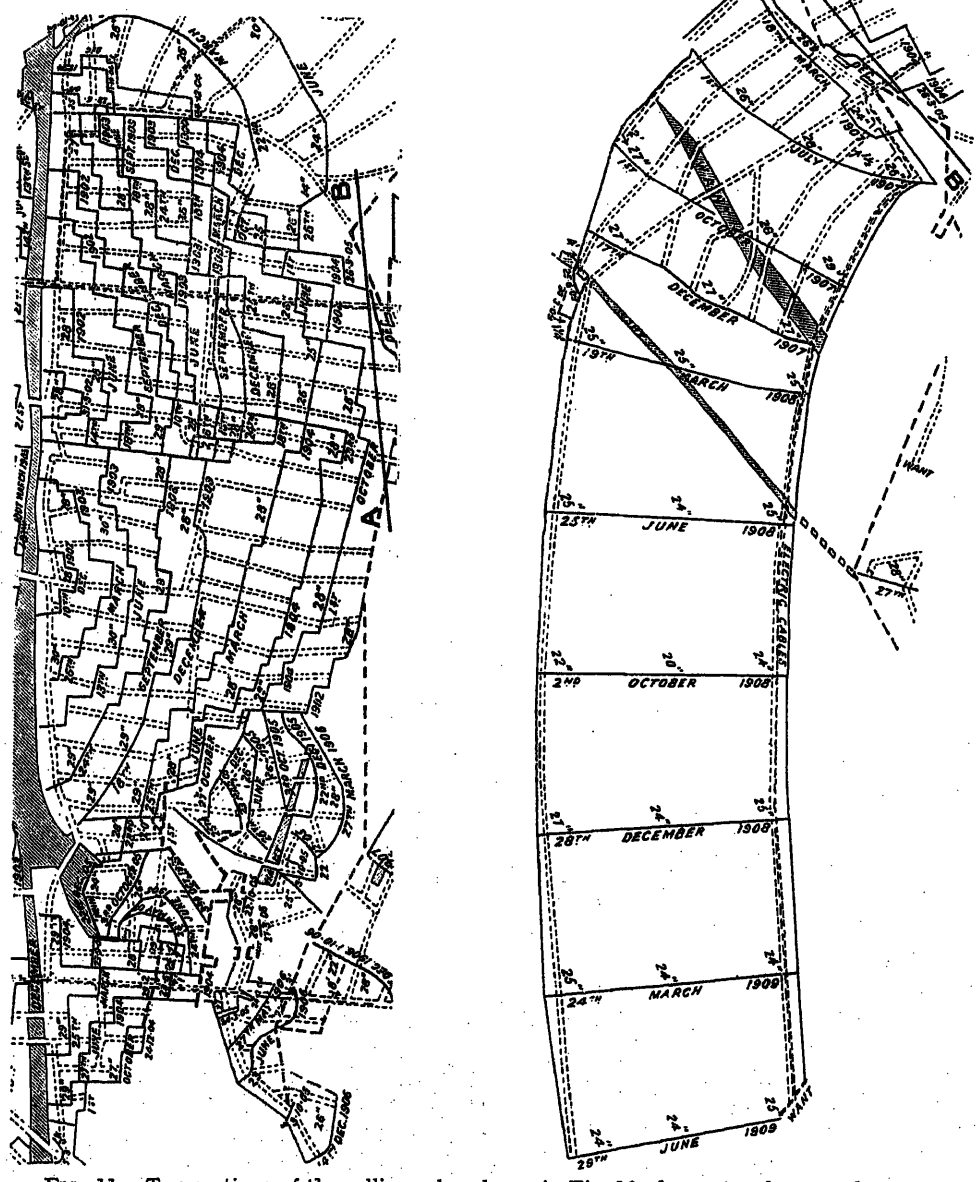


FIG. 11.—Two sections of the colliery plan shown in Fig. 10, drawn to a larger scale.

All the above examples relate to workings on the long-wall principle in this country. So far no economic advantage has been possible from installing a system of conveyors when the workings are pillar and stall, since in our comparatively thin seams the output from any place is not sufficient to justify the first cost and upkeep of a conveyor. In many of the comparatively thick seams worked in the United States the case is different, and conveyors can be economically installed even in room and pillar workings.

The following description of what is probably the longest underground conveyor in use anywhere is included, not as being typical of what can generally be economically accomplished by conveyors, but to show how special circumstances may make it advantageous to use conveyors in a way which would ordinarily be considered quite abnormal. From a coal mine in America an output of 8 500 tons a day was required to be loaded into barges on a river at a considerable distance from the pit; difficulties in obtaining the necessary way-

leaves, and engineering difficulties due to the unstable nature of the river bank, made it inadvisable to carry this output above ground. Extending from the mine to the river, however, was another coal mine which was practically exhausted, and two roads ran from the new pit to the river bank, a distance of over 4 miles. The question was considered of widening and improving these roads, which were in a bad condition, to make them suitable for electric locomotive haulage, but the cost and the difficulties of handling the number of cars which would be required for this output eventually resulted in a system of belt conveyors being installed along one of these roads, thus allowing of the full output being conveyed in one comparatively narrow road, the cost of preparing and maintaining which would be only a fraction of what would have been required had the electric locomotive scheme been adopted. Twenty belt conveyors work along this road in series, i.e. there are 20 complete units feeding on to one another to form one conveyor. The longest conveyor is 504 yards, but varying lengths are required, as the old roadway is not straight; the average length of the conveyors is about 400 yards. The conveyors are of the troughed belt type, the belts being 48 in. wide. Very special consideration had to be given to the belt carriers so as to reduce friction to a minimum. The importance of this will be realized when it is considered that the number of carriers in the total length of conveyor amounts to 6 600. Every bearing throughout all the installation is either a ball or a roller bearing, and special arrangements have been made for regular lubrication. The motors driving the conveyors are situated in rooms constructed at each side of the road, and the power supply is at 2 300 volts, 60 cycles, the motors running at 900 r.p.m.

As the result of actual working it has been found that not only was the initial cost of the belt conveyor system less than that of locomotive haulage, but there is also a considerable saving in running costs.

Conclusion.

It is hoped that this paper will prove of value in indicating to electrical engineers the progress which has taken place in recent years in the mechanical handling of coal underground. Broadly speaking, European conditions have been covered by it and there is no doubt that the best-equipped collieries in Britain now compare favourably with any European colliery on the basis of output per man employed.

Since 1918 the number of underground conveyors in use in this country has increased more than 5-fold, and the rate of progress is still increasing; it is not an overstatement of fact to say that conveying is one of the most important developments in coal-mining, and that the economies accruing therefrom are, as yet, only partially realized.

In one sense the concentration of the whole output of a district on to one or two faces, with an intensive conveying system, may be open to the objection that it is putting all one's eggs into one basket, and it is true that any serious derangement of the conveyor system may temporarily stop the whole output, but it is submitted that it is better to put all one's eggs into one big basket which has been constructed on engineering lines to begin with, and which is of such vital importance that it is necessarily under the constant supervision of the management and staff, than to scatter them into a dozen small baskets which are not under close supervision and any of which may have been leaking eggs for a considerable time before their defects are realized.

The results of using underground conveyor systems on a large scale leave no doubt as to the big basket being the best in this case.

The authors' acknowledgments are due to the South Wales Institute of Engineers for permission to reproduce some of the illustrations which had already appeared in their *Proceedings*.

Discussion before The Institution, 11th February, 1932.

Mr. J. Wayne-Morgan: While I agree with the authors that machine mining would greatly improve the output per man, my own experience has been that there is a great deal of opposition to it, both on the part of the managements and on that of the men. The introduction of mechanical conveyors and coal-cutting will probably entail an entire rearrangement of the price lists, and a manager who has a good price list objects to having to meet the men's committee to rearrange it, particularly as the introduction of something new will probably encourage the men to insist on better terms. A good collier is quite capable of earning his living wherever he has to work, whereas the introduction of machine mining and especially of machine conveying means that the whole output of the coal face has to be pooled, and the good miner has to work harder to make up for the deficiencies of the bad one. When all the coal is put into conveyors the colliery manager is unable to detect the miner who loads small or dirty coal. I have found that these objections are very hard to overcome in South Wales. Although we have tried in several cases to introduce conveyors and coal-cutters, we have always been prevented from doing so by the fact that if machine mining is to come into general use it must be backed up by good team work, which is very hard to get. Unfortunately, in the early days of coal mining in South Wales the only point taken into consideration was which seam could be reached first and which would give the best results financially. When a good seam was found mining engineers did not care what was above or below it; they got out the coal without ever thinking of the future. Ninety per cent of the rubbish in the big tips scattered over the Welsh valleys to-day ought never to have been brought above ground, and it never would have been if the mining engineers of those days had looked ahead a little. The result is that nowadays when we have to work seams above or below those which have been worked and not packed, we have great difficulty at the face in keeping the roof up. Although machine conveying and machine mining call for the longest face possible, it is extremely difficult to get a good face owing to the bad mining work done in

the past. With regard to the future of conveying, I think the belt conveyor will be the most popular in the future. For one thing, it is much more silent that other types, and the collier objects to anything which prevents him from hearing the slightest movement near his working face. At first we had considerable trouble with the belts for these machines, but the quality of the belts has recently been improved and they will now last several years. It is important to ensure that the belt tension is kept as low as possible, and in this connection a useful arrangement to adopt is that of a tension pulley with a spring device attached. Finally, if we are to have machine mining we must have much better lighting, and there are many types of electric lamps now on the market which could be used for this purpose.

Mr. J. A. B. Horsley: The following figures show the use made of conveyors and loaders in British mines in 1930. There were 483 mines using 4 200 conveyors and loaders, 2 050 of these being driven by electricity and 2 150 by compressed air. The distribution as between electricity and compressed air varies very much with the coalfield. In Scotland, out of a total of 829, 796 were driven by electricity and 33 by air. For England with North Wales, out of a total of 2 389, 1 242 were driven by electricity and 1 147 by air. In South Wales, out of a total of 982, 12 were driven by electricity and 970 by compressed air. In the North-Western Inspection Division, which includes the important coalfield of Lancashire, only 10 per cent of the conveyors and loaders were driven electrically. In Yorkshire the corresponding figure was 35 per cent. The authors state that squirrel-cage motors switched straight on to the line are used almost exclusively for coal-face machinery where alternating current is available. It is interesting that this came about from the reluctance of the users to keep in repair starting resistances and auto-transformers. The limitations of space at the machine are severe and therefore it is advantageous to use remote-control starters, which reduce the risk of shock and of explosion because the less frequently apparatus requires to be opened or attended to, the less likelihood is there of accident. The drawback from which the d.c. motor suffers is obvious, not only in manual starting but also in the application of automatic control and electrical interlocks. While it is true that alternating current predominates in this country, direct current is still extensively used. Some 20 per cent of the total horse-power of electric motors installed in mines in Great Britain is still served by direct current, and for Scotland (the scene of the most active development of machine mining, at any rate in the past) the corresponding figure is between 30 and 40 per cent. From time to time fears are expressed in influential quarters as to the risk of explosion to which the workmen are exposed through the use of electricity at the coal face. For the 10 years ending 1929 there were 15 explosions attributable to electricity, causing the loss of 38 lives; these figures compare favourably with corresponding data from abroad. As the authors mention, it is not difficult to design equipment that is flame-proof initially, but the problem of adequate maintenance awaits solution at the hands of the users.

Mr. D. B. Hoseason: I agree that in general the belt-type conveyor produces the best results when operating in the gate roads. For use on the coal face, however, I should like to illustrate the principle of a special type of scraper conveyor (see Fig. A). The chain supporting the cross-members travels along the coal face, dragging the coal with it, and then travels back in the other direction in the vertical steel channel. Actual experience of the working of shaker, belt, and this type of conveyor shows that the individual "fillers" are able to deal with a longer face when operating with this conveyor than with either of the other two, because this type obtains its loading vertically by gravity. The coal is got by operating on the face with a pick instead of by shovelling and lifting, as with belt and shaker conveyors. Gravity really constitutes the loader, and therefore the labour necessary is much less than with the other types. Moreover, in setting up the shaker conveyor or the band conveyor one must leave a minimum of 2 ft. between face and conveyor: thus the filler

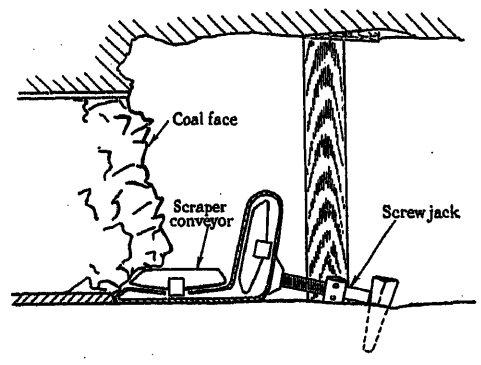


FIG. A.—Scraper conveyor at coal face.

works at first in a very cramped space, lifting the coal and shovelling it into the conveyor. As the face recedes, however, the loading distance increases and at the end of the shift the coal has probably to be moved as much as 6 ft. This point was brought out by one of the photographs shown by the authors. In the case of the scraper conveyor, the conveyor trough is jacked steadily forward as the face recedes. While I agree that the power required for working the scraper conveyor is appreciably higher than for belt conveyors, I do not think that the power consumption per ton of coal raised is seriously affected by the conveying equipment. I can assure Mr. Wayne-Morgan, moreover, that the amount of noise emitted from a scraper conveyor is negligible. Most of the noise near the coal face is usually contributed by the loaders. My second point, with regard to motors for driving conveyors and gate-end loaders, is to emphasize the authors' statements concerning mechanical construction. Practically everything else in the design must be subservient to the mechanical features of the equipment, and it has been interesting during the past 18 months to watch the development of what has become known as the "steel barrel" motor. Fig. B shows one of these machines. It is made from steel boiler-plate, and consequently will not crack under a fall of roof. One advantage of the steel frame is that it enables electric welding to be used by the colliery authorities, and it is generally left

to the colliery staff to weld on fixing appliances wherever they may need them. It will be noted that the laminations are mounted direct in the carcase with a view to dissipating the heat as effectively as possible, in order to reduce the size to an absolute minimum. The bearings of this class of motor are also of considerable importance. In order to obviate the possible entry of dirt and dust into the ball and roller bearings these are enclosed in a cartridge housing independent of the end plates of the machine. The object is to enable the dismantling and inspection to be done without exposing the bearings to atmospheric conditions. In conclusion, I feel that the use of conveyors below ground should be developed as rapidly as possible, because the more conveyors we use in mining the fewer lives we endanger in obtaining the coal which is required. Although temporary unemployment may arise, the more extended use of machine mining must ultimately lead to a healthier and a wealthier nation.

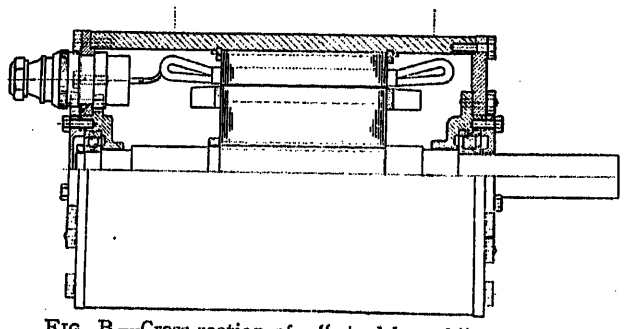


FIG. B.—Cross-section of a "steel barrel" conveyor.

Mr. H. C. Jenkins: Contrary to the statement on page 146 that the first shaker conveyors in Germany were operated by boys, I have a record of the fact that in 1899 the Zwickauer Oberhohndorfer Steinkohlenbauverein were the first to introduce a shaker conveyor hung on chains, and that this was operated by a small single-cylinder air engine, fitted with a flywheel. No further development was made in this direction until about the year 1905, when advances took place in both Germany and Belgium. The earliest record I can trace of a boy being employed to work a shaker conveyor by hand is a reference to some shakers in use on the Rand in 1908. I should like to ask the authors how they propose to use an end drive at the bottom of the conveyor, as mentioned on page 147: I had always understood that this could only be applied at the top of the conveyor. On page 148 they state that shakers have been used for conveying coal up a gradient of 1 in 20, but I have actually seen 40 tons per hour delivered up a gradient of 1 in 8 to 1 in 10. Shaker conveyors up to 150 yards long are working satisfactorily to-day. As regards the statement on page 148 that the first belt conveyors failed because of the extravagant cost due to belt wear, 10 years ago if a belt lasted 6 to 7 months under coal-face conditions it was considered to be satisfactory, but improved methods of construction both of the belt and of the mechanical part of the gear have increased the life of the belt 4 to 6 times. On page 149 the authors mention that special loaders or short lengths of shaker conveyors are frequently used to deliver on to the gate belt. While this is technically correct, not more than 10 or 15 per cent of the gate-belt conveyors at work in this country adopt this method. The modern type of tension drum is usually moved up each day, thus doing away with the added expense of the special loader. I do not agree that a double-drum type driving gear is a necessity for face work, as there are a larger number of special single-drum driving gears working on the coal face to-day the design of which is so arranged that "creep" between the belt and driving drum is eliminated. As to the authors' view (page 150) that only chain scraper conveyors can be used on gradients in excess of 18°, I would point out that belt conveyors are working to-day on gradients of 20°, and if a chain scraper will work on such a steep gradient I am quite sure that a belt conveyor will convey the coal more economically on the same gradient. Belt conveyors are also working under wet conditions, being fitted with a special device to overcome the tendency to slip on the driving drum. It is economically much better to use a belt conveyor, as experience has shown me that the horse-power necessary to work the latter is only one-fifth of that required to operate a chain scraper. The shaker driving gear with a bell-crank arm shown in Figs. 5 and 6 is surely becoming out-of-date, owing to the difficulties which it involves. Of the total number of shaker conveyors employed in this country only a small percentage embody this type of drive. I am not clear about Fig. 7, which shows a gate conveyor 240 yards long with a balance arrangement fitted to the driving engine. Is this 240-yard shaker gate conveyor driven by a single engine? As regards switchgear (pages 153 and 154), while I agree that the push-button type of control is the ideal, owing to the heavy expense involved very few of these equipments are actually in use. Could the authors state what relation between starting torque and running torque they find most satisfactory for use with the conveyor motors they are installing? Regarding the relative merits of a.c. and d.c. motors for driving coal-face machinery (page 156), in many cases it has been found that collieries fitted with d.c. plant have had a longer experience of underground machine mining and their officials are giving the equipment better treatment. I should like to know whether the authors can confirm this from their experience. The case mentioned on page 158, where a colliery was changed over in 3 weeks from hand to machine mining, is surely a very exceptional one. As a rule it takes from 1 to 2 years to effect such a change-over in connection with a large colliery. The Frick conveyor installation in the United States (see page 159) is surely an exact duplicate of a standard surface installation put into a special tunnel underground. In their Conclusion the authors suggest that the use of an intensive conveying system is like "putting all one's eggs into one basket"; a large number of colliery companies are, however, fully satisfied that the modern belt conveyor is sufficiently reliable to do this. I know of cases where underground belt conveyors have been at work from 1 to 2 years without a single involuntary stoppage. In many instances they constitute the most reliable form of underground transport. There is no doubt that British manufacturers have given a lead in underground belt-conveying, par-

ticularly to Continental and American mines. Perhaps this type of conveyor has been more applicable to our own than to foreign conditions; the more extensive use of electricity underground in connection with longwall working has also aided the development of British conveying equipment.

Mr. A. R. Cooper (*communicated*): It is suggested in the paper, and is certainly borne out in practice, that the overall dimensions of a driving unit should be kept as small as possible. The compression of a driving unit into the smallest possible space has, however, a number of attendant disadvantages. For instance, I suggest that instead of a motor being built integral with its gearbox it should be connected to it by a simple coupling, or a universal joint, so that by removing three bolts, or, better still, a single pin, it would be possible to disconnect the motor from its gears. This arrangement would possess the following advantages. (*a*) It would remove the danger of oil working back from the gearbox into the motor. (*b*) It would facilitate the changing of motors in the event of a breakdown. (*c*) It would enable the electrician to determine in the shortest possible time whether the trouble was mechanical or electrical. This would be a decided advantage where shaker conveyors are used, for when a conveyor of this type breaks down the trouble is usually due to driving rods hitting the floor, conveyor pans becoming fast, or bearings becoming seized up. I should like an expression of the authors' opinion regarding overload protection. The high-torque squirrel-cage motor is undoubtedly the most desirable form of prime mover for underground conveyors, but it has the disadvantage that high starting currents are taken from the line. To cope with these peak currents it is necessary either to fit the solenoid type of overload protection with long time-lags or to set the protective devices to trip at abnormally high values. In practice it is usually found that this type of overload device is set to operate at current values as much as 150 per cent in excess of the normal working load, making it possible for a motor to work with a continuous overload of about 100 per cent without cutting off the supply. Would the thermal type of overload, if it could be suitably applied, solve this problem? With reference to the interlocking of conveyors, is it not probable that by taking such pains to make the electrical apparatus foolproof we are introducing a number of disadvantages? The whole purpose of interlocking two conveyors and a loader is to prevent the conveyors delivering their coal on to the loader belt when it is at rest. In practice we almost invariably find that there is a workman near the face-conveyor driving unit who can stop the machine as soon as the loader stops. If a little coal is spilled it is rarely a serious matter, as it can be cleaned up by hand at the end of the shift. By cutting out the interlocks on a system of this nature the switchgear would be considerably simplified, there would be fewer contacts and less wiring to give trouble, and the location of electrical faults would be considerably facilitated. The class of switchgear described in the paper will do, and undoubtedly does, all that is claimed for it, but when it has to work in atmospheres so humid that every switchcase is wet with internal condensation, when a fault on the interlock wiring can shut down all three machines, and when this fault has to be located by the type of underground electrician prevalent a few years ago, I should certainly prefer the simplicity of three standard conveyor controls with the possibility, if the worst occurred, of having to dig out the loading end of a gate-end conveyor.

[The authors' reply to this discussion will be found on page 167.]

North-Eastern Centre, at Newcastle, 8th February, 1932.

Mr. S. Burns: The general adoption of intensive machine mining has enhanced the difficulty of transporting coal from the face to the haulage landings, owing to the resultant rapid rate of advance of the working faces. The ultra-modern appliances described by the authors represent only the beginning of the struggle to overcome the increasing difficulties of mining thin seams of coal not worked by preceding generations. I am surprised that the paper does not include among the advantages of machine mining absence from electrical and mechanical breakdown. In designing conveyors the problem is to rectify faults without at the same time introducing others which are just as troublesome; for example, a real danger was removed by enclosing the lower belt of a belt conveyor to prevent spillage on to it, with the result that when a fracture of this belt does develop its location and repair are rendered more difficult than ever. I suggest that the manufacturer of machine-mining equipment should resist the natural temptation to be continually effecting so-called "improvements" to the detail design of his plant; that he should keep a properly indexed record of complaints on the one hand and of renewals orders on the other; and that only those parts should be modified in regard to which complaints have been justified by replacement orders. Although frequency standardization is not mentioned in the paper, it is important that coal-face machinery sold into this area during the next few years should be suited for operation by 40/50-cycle inter-frequency motors. The gears and other power-transmission arrangements should be so designed that an ultimate 25 per cent increase of motor speed will not necessitate troublesome structural alterations.

Mr. G. Clephan: The authors state that by means of shakers it is possible to convey coal up a gradient as great as 1 in 20, but while I agree that this can be done I feel sure that uphill conveying is not a commercial proposition. What are the practical limits of use of shaker conveyors? In my opinion, except where the gradient is regular and approximately 1 in 18 in favour of the load, or steeper, the belt conveyor is a better proposition. The modern improvements in belt-conveying have restricted the field of use of the shaker conveyor to conditions highly favourable to it, and its application is gradually becoming more and more restricted. According to the authors' opening remarks,

belt conveyors still embody defects that were eradicated from surface plant twenty years ago. I should be glad of some further information on this point, as many of the surface belts running in collieries to-day are, I consider, worse from the engineering point of view than anything of the kind I have ever seen underground. With regard to the life of face belts, I should welcome any information as to the progress of research on rubber belts. Why do the authors condemn the use of flat-belt conveyors except at the coal face? Although I agree that the flat belt is not so perfect as a troughed belt, in practice the difference is not so marked as they suggest. I have found that troughed centre-gate belts require much more attention and alignment than is indicated in the paper. With regard to the loading of coal from one conveyor to another at right angles, what do the authors consider to be the most satisfactory method, apart from the use of a telescopic scraper loader? Also, what is the maximum length over which it is economically possible to convey coal with belts? Has this length increased since the Frick installation was laid down in the United States? I consider that in the colliery of the future the coal will be conveyed to the shaft bottom on belts. With regard to the question of remote control of conveyors, it would be interesting to know whether any reliable data are yet available as to the first cost and maintenance of the two systems. While underground conveyors have many economic advantages, without the necessary organization behind it no conveying system can be made a financial success. The collieries are handicapped in this direction because the staff has to be built up from the beginning from unskilled labour, a fact which is often ignored by both the manufacturer of conveyors and the electrical engineer.

Mr. R. W. Mann: Five or six years ago the mining manufacturing industry ridiculed remote control, yet it is now preferred to a system of switch-fuses. I should like to see the use of switch-fuses entirely abandoned, particularly as it is doubtful whether they meet the requirements of the Memorandum on the Regulations as to the use of Electricity in Mines, which calls for a piece of apparatus capable of isolating the supply under all fault conditions. Of the multi-panel system of control, I would say that this is developing on lines which wide experience suggests are wrong. The practical requirements of pit conditions necessitate the continual changing both of methods of control and of the apparatus to be controlled; the necessary flexibility is only obtained by single-unit equipments. The system of multi-control shown in Fig. 8 has the following drawbacks. (*a*) One isolating switch interrupts power to all circuits. (*b*) A leakage fault on one unit shuts down the entire equipment and does not indicate the circuit on which the fault occurred. This is also true of interlocked overload tripping. (*c*) The master controller ties the groups of three permanently together. (*d*) The system of intermediate contact for short-circuiting the choke reset coil is impracticable in operation, as the rapid movement of the contact finger does not always give sufficient time for the operation of the contactor. (*e*) Direct-acting leakage does not give fine enough settings and does not appear to discriminate visually between overload faults: furthermore, from the diagram it would appear to be self-resetting, so that the operator could reclose the contactor under fault conditions. As regards the auxiliary switch working in conjunction with the motor isolating switch (see page 154), this interlock will probably race the contactor on fast operation of the isolating switch. Turning to the subject of motors, the design requirements of machines for driving all types of conveyors are similar in many respects, and suitable ratings for such motors can be, and have been, determined. In their statement of the problem for the designer: "Given the maximum dimension which may be used, put into that space the most powerful motor that can be obtained," what do the authors mean by "powerful"? I can design a 10-h.p. motor to take up half the space occupied by a 5-h.p. motor having the same working speed. The appropriate rating of a machine to suit a given purpose can only be arrived at by a complete technical investigation of the requirements: trial-and-error methods take far too long. In my opinion there is no reason why colliery engineers should not be able to specify a motor having a definite horsepower, speed, and rating, and apply such a machine to any orthodox type of conveyor. The time will come when a mining-conveyor manufacturer will find it unnecessary to use a special built-in motor of unorthodox design and rating.

Captain S. Walton-Brown: I shall confine my remarks to the drag bucket scraper, or scraper loader, which I was the first to introduce underground into Great Britain. Equipment of this character has been regularly working at Seghill colliery since the beginning of 1928. Subsequent to its introduction at Seghill the scraping system was employed for heading purposes in the driving of the Halkyn drainage tunnel in South Wales, and also for the Grampians power scheme. During 1929 other collieries commenced to utilize scraper loaders, and the number of such installations is now steadily increasing. An important factor involved is that the scraper scoop is either wholly or partly self-loading, and always self-emptying; I shall return to this point later on. The three other types of conveyor referred to by the authors all become costly to work when the height of the coal seam falls below 2 ft., and for such seams it has at many collieries been the practice to revert to gate-way working as being the more economical method. The scraper loader has altered this situation. It also operates on gradients on which other types will not function, and it involves a very low cost for moving up. The system is still in its early days in Great Britain, and it will probably be much improved during the next few years. The V-type, as we employ it under a good roof, requires a clear space (without roof supports) of 6 to 8 ft. from the cut face. The face is shot down and the scoop started. The hinged end travels inbye along the face and on the return journey the open mouth meets the coal, or is kicked into the pile of coal and loads itself. The whole face can be loaded without manhandling any of the coal, thereby saving both time and energy. At the discharge point the scoop empties itself into tubs, conveyors, or another scoop system. The box type with hinged flap usually requires a good proportion of the coal to be moved into the fixed path in which it runs, but the coal has only to be slid and not lifted. Much larger pieces of coal can be handled with this type than with

the other types of conveyors mentioned in the paper. I do not agree that the scraper loader is subject to the limitations stated by the authors. Faces up to 100 yards long on each side of a mother-gate can be worked in the same way as with other conveyors. If increased capacity is desired, or the bottom is soft or wet, my method is to run the scoop in a light trough with low sides which is set on the floor and is capable of being easily moved up. As a result of the action of the troughing a short scoop is practically converted into a very long one, and 3 or 4 tons of coal at a time can easily be slid along the trough to the delivery point. If the trip along the face is considered to be too long, two scoops are fitted in tandem on the same rope so that each covers rather more than half the face, the far scoop leaving its load just past the centre and the second scoop picking it up and delivering it at the discharge point. As a single trip for a 100-yard face (in and out) takes less than 3 minutes (assuming a scoop speed of 100 yards per min.), if 3 or 4 tons are handled on one trip it does not take long to move 100 tons. With scoops in tandem the time can be halved. By placing a number of scoops in series in the trough and reciprocating them over any given short distance, a steadily-moving delivery system with adequate capacity is provided. As with other types of conveyors, it is essential that the men should be thoroughly trained, fond of machinery, and anxious to take care of it, realizing that in return the machine will do all the hard work and give them satisfactory earnings. The scraper loader system is much more economical than other types in canch work at the head end where discharge takes place, as no extra height has to be made. While the motor employed is of a larger horse-power than in the case of other types of conveyors, the total cost for power used in running is small and the item is not of great importance in view of other economies. The scraper loader is of service in any system of mining, and it can be advantageously utilized in bord and pillar so as to serve several headings, as the haulage can be moved from one place to another during the course of the shift. This cannot be done with the other types. By the use of a third drum on the hauler the scoop can be made to operate around corners and so travel the mother-gate as well as the face. The driving of drifts can be greatly speeded-up by the use of scraper loaders for the purpose of removing the loose material after blasting. On the faces we have hitherto used conveyors of one of the first three types mentioned by the authors, followed by rope haulage to the shafts: before long, however, the order may be reversed—so as to utilize rope haulage (in the form of the scraper loader) on the faces and one of the other types of conveyors (in my view the belt type) towards the shafts.

Mr. H. W. Clothier (*communicated*): I should like to refer first to some of the mechanical difficulties encountered in moving the coal from the face. The shaker or jigger conveyor has a hard jerky action which is bad for any type of mechanism. The belt type runs more smoothly, but it is dependent upon material which seems unsuitable for such hard wear. The scraper types have to provide for the return of the scrapers or buckets. An alternative, which has been proposed by a local engineer who works at the coal face, might be called a "pusher" type. The trough is made to reciprocate at an even steady motion, slowing down at each end of the stroke, and the coal is pushed along the trough by plates which hinge in the form of a non-return valve. Whilst this conveyor may prove to have disadvantages of its own, it would appear to be worth a trial as a means of overcoming some of the objections to the types described in the paper. The author seems to retain a regard for the simple drum-switch and fuse protection, but I agree with Mr. Mann that fuses are inadequate. The question of renewal of fuses also gives rise to some difficulty, as either spare fuses of correct rating have to be stored in a compartment in the switch fuse-box or the renewal of the fuse is dependent upon the presence of a responsible person who, even if available, may not have the correct size of wire with him. This gives rise to the danger of fuses being renewed by wire of unsuitable rating. Moreover, as stated in the paper, with merely mechanical interlocking at the motor switch there is nothing to prevent the plug from being pulled out even if the gate-end switch has been left on, the plug therefore remaining alive. Effective electrical interlocks have been successfully applied in a number of cases without the additional elaboration of complete remote control for the coal-cutter or conveyor motor. In their spoken abstract of the paper the authors mentioned oil circuit-breakers, and I would point out that these are in extensive use for gate-end service, particularly for coal-cutters; conditions are similar for conveyor circuits. The advantages of the oil circuit-breaker cannot be overlooked: for example, the immersion of insulation reduces the internal clearances, and therefore the overall dimensions, for a given breaking capacity. Thus, as compared with air-break contactors, oil circuit-breakers are more competent to withstand the impulse stresses to which they may be subjected in dealing with short-circuit currents, and the smaller volume for the intake of explosive gases means less risk of such gases exploding than in the large enclosure required for air-break contactors of the type shown in Fig. 8. The requirement in regard to strength of enclosure is at present under discussion, and in this connection the relative air spaces enclosed in the various types are of paramount importance. The operating conditions—particularly in thin seams—emphasize the need for remote control, and this need cannot be met in a "simple" manner. For reasons of economy the trend of development is along the lines of air-break contactor starting gear backed up by oil circuit-breakers at distributing centres. The scheme of connections might be such that the oil circuit-breaker dealt with short-circuit faults, and the contactors only with overloads, with thermal time-limit control. It is satisfactory to note that the British Standard plug (B.S.S. No. 279) is becoming increasingly popular. The fact that other makes of plugs are, as mentioned in the paper, heavier and more cumbersome is a testimony to the work of a Standardization Committee. Amongst colliery engineers there appears to be a wide diversity of opinion on what is the most suitable apparatus to meet the conditions, even in adjacent mines in the same coalfield. This applies not only to conveyor plant but to electrical applications in general, and particularly to switching requirements.

Mr. E. E. Grover (*communicated*): I do not agree with the statement (page 156) that " there is no difficulty in complying with all the requirements for flameproof enclosure contained in the British Standard Specifications for flameproof enclosure (No. 229) and for motors for use in mines (No. 270)." B.S.S. No. 270 calls for terminals to be external to the flameproof enclosure, a desirable feature which cannot easily be achieved on some types of conveyor motors. One method is of meeting this requirement by means of a detachable dividing box which can be withdrawn like a plug from the stator terminals. In the section dealing with switchgear no mention is made of the difficulties which are experienced by manufacturers in constructing flameproof enclosures. One of the requirements for a flameproof enclosure mentioned in the Appendices of B.S.S. Nos. 126 and 127, is that the enclosure shall withstand an internal pressure of 110 lb. per sq. in. I do not agree with the authors' statement that there is no difficulty in complying with this requirement, and I should be interested to know how such compliance is achieved. Fig. 8, which is intended to illustrate a system of remote control applied to three units, shows earth-leakage protection on the switch controlling the loader. This is the wrong position for such protection, as it is preferable to keep the gate-end switch as simple as possible. The better position for the leakage trip is on the next outbye switch controlling the supply to the 3-panel board. The only advantage of fitting each conveyor and loader panel with earth-leakage protection would be to obtain selective protection, but it would not be satisfactory to shut down the loader motor and keep the conveyor motors running.

[The authors' reply to this discussion will be found on page 167.]

Scottish Centre, at Glasgow, 12th April, 1932.

Mr. J. Bentley: Although motors used in colliery work underground have to stand a great deal of ill usage, I do not see why such motors should not comply with the appropriate British Standard Specification. The motors, although of special design, have to be made to give an output, the horse-power and rating of which can be estimated. By using Class A insulation the temperature rating can be fixed at a high figure; in fact, some of the motors made for the Admiralty have to work at an ambient temperature of 150° F. and have a final temperature of about 200° F. The design should be controlled by the use of the most economical materials in respect of weight and space factor. The cost of materials and labour should be regarded as of only secondary importance. What appears to be required is a motor which will give a relatively high torque for starting and overcoming momentary overloads, and which will stall should the torque exceed a safe limit. These requirements call for the use of some such system as the constant-current or Ward-Leonard. The cost of stoppages due to breakdown must be credited to the capital-outlay account. The motor should have a high starting torque in order to overcome the difficulties of high static friction, momentum, and momentary overloads. To obtain this feature other desirable characteristics have to be sacrificed; unless an auto-transformer starter is used excessive stresses are put on the gearing, owing to the motor starting up with a jerk. The use of slipping clutches to solve this problem is well worthy of consideration. These clutches are used extensively on ship deck machinery to get over similar difficulties. The small angular slip gives an appreciable extra torque from the armature momentum without overloading the motor. These slipping clutches do not, however, help in the case of sustained excess torque; they are only designed to avoid excessive stresses on the gearing until the overload release acts. Overload releases do not save the gear from excessive stresses, as the overload is applied before the release operates. The use of the crank motion in combination with the flywheel, as advocated by the authors, successfully overcomes the difficulty of momentary overloads. The crank provides extra torque at a certain part of its stroke to replace any loss of kinetic energy of the flywheel due to overloads. If the flywheel could be started up after the motor had got up speed, the crank motion would also help considerably to reduce the starting torque required.

Mr. W. J. Cooper: I should like to refer to an incident which happened many years ago, in order to indicate the magnitude of the difficulties with which the designer of electrical plant has to contend. I was called out in the middle of the night to attend to a defect in some colliery machinery, and with some difficulty I got as far as the gate-end boxes. I discovered that the designer of the fuse gear had unfortunately provided a space in the jaws of the latter which fitted the half of a collier's pick. The operators informed me that when a coal-cutter became jammed by a fall of coal the pick head allowed the motor to clear the cutter.

Mr. J. Gogan: Manufacturers have placed in the hands of colliery engineers plant which satisfactorily meets the demands made upon it. However, I see no reason why motors of a standard horse-power should not be used in conjunction with coal-conveying plant.

Mr. P. W. Yuille: I should like to know whether anyone has ever suggested a scheme whereby the electrical drive could be retained at a distance from the coal-face and the power transmitted by means of a fluid such as water. Has a development of the system put forward during the War by Mr. Georges Constantinesco ever been adapted for underground work? This system has the advantage that it will allow of all electrical gear associated with conveying plant being kept away from the coal-face, thus eliminating fire risks. Regarding the method of motor drive for limiting the starting current, would not a hydraulic-turbine-cum-pump drive be suitable for this purpose? Such gears are now made totally enclosed in one casing, and are very robust.

Mr. R. E. Keelan: I should be glad if the authors would say what is the power factor of a.c. coal-cutters, in view of the fact that, according to the authors, they have to be capable of developing from 100 to 250 per cent starting torque, and possess extraordinary high

stalling-torque characteristics, to say nothing of their having to be capable of working frequently to stalling point. Under such circumstances it would appear that the power factor would be very bad.

Prof. S. Parker Smith: Are the authors troubled by excessive voltage-drop? It seems to me that in view of the very long drives which are necessary, voltage-drop might be almost a limiting factor, as was the cost of cables. With regard to the cage motors, can sufficient torque be obtained with the single-cage type, or must a double-cage construction be used? It would be interesting to know the starting conditions with which conveyor motors have to contend.

Dr. M. G. Say: In some mines the working faces may be 3 or 4 miles from the shaft, and it would seem that under such circumstances the voltage-drop would be considerable. In ordinary supply practice it appears to be the custom to restrict direct switching of motors to comparatively small sizes. Underground, however, the 30-h.p. size is apparently not too big for this drastic method of starting. I should like to ask whether this practice is usual. Of course, if one could reckon on a line drop of the order of 42 per cent, a star-delta starter would be unnecessary.

Mr. S. Mavor: With reference to the transmission of power by means of fluids, I once discussed with Mr. Constantinesco the application of his system to coal-cutters, and I am satisfied that so far as the wave-generator and the wave-motor are concerned the scheme is feasible. The difficulty at that time was the lack of a flexible pipe suitable for underground service and capable of withstanding the high pressure. Even now a flexible pipe suitable for the purpose does not seem to be available. Proposals have been made from time to time to drive coal-cutters by hydraulic means, but certain practical difficulties associated with hydraulic plant have not yet been overcome. One of these is the danger of water leaking from the joints: in many collieries such leakage would cause disintegration of the strata, and this might be disastrous. Certain classes of shale are converted to mush by contact with water, even in comparatively small quantities. One of the lines of future progress will be in the direction of mechanical loading of face conveyors. This is already an accomplished fact in the thicker seams, and experience will enable us to reduce the limit of thickness of seam in which mechanical loading can be applied.

Mr. D. H. Bishop: In connection with starting by direct switching, has any difficulty been encountered in practice, due to the rapid rate of acceleration? I understand that in America, where direct switching seems to have been frequently employed for industrial purposes, the motor makers recommend that pulleys and belts should be 25 per cent wider than the standard, owing to the wear otherwise produced by belt slip during starting periods. Do the belts of the conveyors suffer in any way due to this cause? I have found from experience in cases where direct switching is carried out for very frequent starts, that designers do not always appreciate the abnormal amount of heating produced in the motors. This point should not be forgotten when laying out an installation. With slip-ring motors, of course, conditions are very different; much of the heat produced is external to the motor, and the current-rushes are smaller. Do the authors incorporate any extra resistance in the rotors of mining motors?

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, AND GLASGOW.

Messrs. W. B. Hird and **J. B. Mavor** (*in reply*): Mr. Wayne-Morgan has given us a rather pessimistic view of the position of mechanical conveying and coal-cutting in one particular district, but this is far from being typical of the attitude of management or men throughout the country.

We are confident that we are expressing the feelings of members in thanking Mr. Horsley for the valuable statistics he has put forward.

In reply to Mr. Hoseason, the conveyor described has so far proved to be very limited in its application. General mining conditions in this country do not appear to lend themselves to its successful use. The motor described by Mr. Hoseason is a robust construction, but the space required by such a motor is a serious disadvantage.

In reply to Mr. Cooper, who inquires as to the registering of motors on the gearcases, it is suggested that the advantages from doing this far outweigh the disadvantages mentioned. The motors can be secured by four or five bolts or set-pins and require no holding-down bolts, so that it is really more simple to remove the spigot-registered motor than the motor with a flexible coupling. It is submitted that it is not possible to make a base-plate to carry the motor independent of the gear which will withstand the strains imposed upon it by pressure from roof props or due to heaving pavement.

Theoretically the thermal type of overload protection most nearly conforms to electrical requirements, but in practice the mechanical limitations of the thermal strip and the necessary heating element result in construction much less robust and suitable to mining conditions than those usually associated with the best designs of solenoid trips with time-lags of the oil dashpot type. The most satisfactory form of overload protection so far used is the circuit breaker with the solenoid type of time-lag. With the high-torque motors now in use starting is so rapid that the time-lags do not need to be set nearly so high as heretofore. When outputs approaching 600 or 700 tons per shift are being brought to one loading point, sequence control of the conveyors is essential. With a properly sequence-controlled conveyor unit, the attendant at the junction of the conveyors has time to spare to fill coal and therefore be on the productive wage list. There are now many instances of sequence-control equipments of this kind which have functioned in a trouble-free manner over long periods. The added complication is not great and the economies are material. We agree with Mr. Cooper that it is thoroughly wrong to complicate either a conveying or a conveying-control system unless the savings resulting from such complications can be clearly defined.

Replying to Mr. Jenkins, we agree that special loaders or short lengths of shaker conveyors are not essential in

the operation of gate-belt conveyors. Nevertheless, it is at all times desirable, from the point of view of belt life, to load the belt in the direction of travel. In most cases nowadays, however, it is considered more expedient simply to load the belt direct from the face conveyors without any connecting link. The only other device known to us as a substitute for the double driving drum, where small-diameter driving drums are in use, is one in which the belt is held in contact with the driving drum by means of a spring-loaded roller. On a normal conveyor the duty of the belt is to carry the load and transmit the power necessary to transport the load. It may be in the future that the technique of belt manufacture will permit of the mangling stress set up by a roller of this kind without any destructive results, but belts as at present constructed are very liable to be damaged if rolled between two rollers as described.

We are aware that a large number of belt conveyors are working to-day on gradients as high as 20°, but as this is just a fraction beyond the normal angle of repose of coal on a conveyor belt 20° may be taken as the limit, and even at this angle success or failure may depend on the character of the material being conveyed.

We agree with Mr. Jenkins that, wherever possible, the belt conveyor is to be preferred to the chain flight scraper conveyor, but when the gradients become too steep it is necessary to use chain flight scraper conveyors with special flights to meet such conditions. We are aware of belt conveyors a considerable section of which is running under water, but this is an altogether undesirable case for belt service, because of the impaired belt life. Mr. Jackson mentions a device for avoiding belt slip, but as the belt gets cut and abraded each cut and abrasion is a point at which the water can get in to destroy the belt.

Figs. 5 and 6 were simply inserted to show the lay-out of the coal faces. The 240-yard conveyor illustrated was actually driven by a single engine over a period of months; back-balances and springs were used as counterweights for the pans on the inclination. It is our experience that in the old-established collieries using direct current the mechanics and electricians are in the main more sympathetic towards machinery underground. As to remote-control switchgear, it is common experience that new devices are in the first instance adopted only by the more progressive firms, but since the introduction of this method of control its use has steadily increased and is now increasing more rapidly as its advantages are realized. In no instance that we know of has remote control equipment, once installed, been replaced by other types. On the contrary, users have extended the use of this method of control. It is difficult to answer the question as to ratio of starting to running torque, because this necessarily varies considerably in different cases, but by the use of special high-torque motors it is possible to get a starting torque of $2\frac{1}{2}$ times the rated full-load torque of the motor. There is no reason why underground belts, in a gate-road especially, should not run for longer periods than one or two years without an involuntary stoppage, and they are doubtless the most reliable form of underground transport when properly designed and installed.

In reply to Mr. Burns, the enclosing of the lower belt has in practice proved a great advantage from the point of view of eliminating unexpected belt breakages. Does Mr. Burns seriously propose that an addition to the design, which minimizes the possibility of stoppage, should be left out because if a stoppage does occur, due to breakage, the addition of the appliance makes the repair a little more troublesome? The designs of underground machinery are actually developed, as he suggests that they should be, from a properly indexed record of complaints and difficulties experienced underground with the machinery. It is agreed, however, that the utmost simplicity possible, making allowance for the proper functioning of the machinery, is desirable before anything else.

Replying to Mr. Clephan, the reason why the troughed belt is preferred to the flat belt wherever it can be used is that without external aids the troughed belt has a carrying capacity 100 per cent greater than the flat belt. The usual practice in underground flat belts is to increase the capacity of the flat belt by using spillplates to enable the load to be piled up as it is in the troughed belt. This means that while conveying is being performed at full capacity the coal piled on the flat belt must of necessity rub along the spillplates. As the belt requires running clearance from the spillplates, spillage between the belt and spillplate when the belt is fully loaded is inevitable. If Mr. Clephan has found in practice that the difference in power required between troughed and flat belt is not very marked, it indicates that his belts are rarely running loaded to full capacity. Tests under duplicate conditions with both types of conveyor set up properly, and conveying each to the full capacity of the troughed belt, revealed that the flat belt requires 50 per cent more power under these circumstances, this power being expended in overcoming friction, which is destructive to the belt. Negligence in maintenance of a troughed belt in a gate-road can lead also to excessive power consumption. We recently had experience of a troughed belt which was using double its designed power for this reason. An hour's attention by the supervisor reduced the load to normal. Care in design and maintenance of belt conveyors, with a special view to the avoidance of friction losses, is always amply repaid in reduced belt maintenance charges. With regard to the maximum economic length over which coal can be conveyed, this depends very largely upon circumstances and environment, also on the amount of coal which has to be conveyed. It is not possible, therefore, to generalize on this subject, but one of the authors was assured on the occasion of his visit to the Frick Belt that under their special conditions they would have put in a belt 10 miles in length, and that their experience with the existing belt justified this decision from an economic standpoint in view of the very large daily output which they handle.

In reply to Mr. Mann, when remote control was first talked about it was received with a considerable amount of caution, but to describe the attitude as one of ridicule is to go far beyond the facts (see our reply to Mr. Jenkins). It is not suggested that remote control is the only alternative to switch fuses. The methods in the paper were given as examples from the simplest to the most advanced forms at present in use, and the mention of

the fact that plain switch and fuse are still in use does not imply any special liking for this method. (This replies also to one of Mr. Clothier's remarks.)

The unit method of control as contrasted with the multi-panel system has some advantages chiefly from the manufacturers' point of view, but the multi-panel system also has compensating advantages, and it is obvious that when dealing with 3-unit conveyors these advantages become paramount. The extended use of multi-panel equipments by collieries having experience with them shows that practical requirements of pit conditions do not necessitate the continual changing Mr. Mann imagines to be the case. The system of multi-control shown diagrammatically in Fig. 8 is merely an example of the latest tendency in matters of control. The general scheme is obviously capable of detailed variation, and Mr. Mann's detailed criticism is therefore rather off the point.

(*a* and *b*) It is obvious that isolating switches and also leakage protection can be introduced in each panel if the user desires it and is willing to pay for it.

(*c*) Of course, the master controller ties the three motors together; that is its purpose, and is necessary to give the fullest control and protection to a 3-unit conveyor of large capacity. Schemes comprising three conveyors and multi-panel control on the general lines indicated have been installed for some years, and have worked daily during that time, and the conveyors are still working together in the same group.

(*d*) Both experiment and actual experience in practice have shown that the switch cannot be manually operated to beat the magnetic relay. Far from being impracticable, numerous examples of the construction have been in successful operation for years.

(*e*) Leakage relays with fine setting can obviously be used instead of direct leakage trips, and without in any way altering the general scheme. Experience in mining conditions, however, soon shows that portable gate-end control gear is not the place for delicate relays, however suitable they may be for stationary equipment outbye, and a somewhat coarser direct trip of robust construction which remains in working order is to be preferred to a fine-set delicate relay apt to be frequently damaged.

Fig. 8 purports to be only a diagram of connections and does not show relatively unimportant details. The actual equipment does, however, provide the visual discrimination Mr. Mann asks for. Moreover, the leakage relay is not self-resetting, and the operator cannot reclose under fault conditions. Mr. Mann's assumption as to the probability of the interlock racing the contactor has been dealt with above.

We are not in agreement with the statement that the time will come when a mining conveyor manufacturer will find it unnecessary to use a special built-in motor, as the tendency appears to be increasingly in the direction of using built-in motors and dealing, therefore, with the motor and conveyor as one unit.

Mr. Mann also asks: "What do the authors mean by the word powerful?" (as applied to the motor). That is the real crux of the difficulty. The horse-power at which a motor is rated should, of course, depend upon its being able to give that power for a specified time without exceeding a specified temperature. The motor of given dimensions which could be rated at the highest horse-power under these conditions would be the most powerful motor. Unfortunately, the operator does not accept this definition, and in 3-phase work he talks of a motor being more powerful if he finds it more difficult to make it stall. He considers a d.c. motor more powerful if he is able to drive it harder and get more coal without making it spark, and it is largely the necessity for meeting such demands, in addition to keeping down temperature-rise under normal working conditions, which makes the design of coalcutter and conveyor motors unorthodox.

In reply to Capt. Walton-Brown, the scraper bucket type of conveyor has certainly a useful place in the conveying system used in this country, but is limited in its application so far to good floor conditions, and relatively small outputs per face unit.

The conveyor described by Mr. Clothier would appear to be limited in its application to seams producing small coal, such as coking coal, because if the size of lump were not controlled jamming and breakage would be prevalent as the flap passed over each pile of coal formed by the reciprocating movement. The drum-type switch with fuse is still in very common use in spite of all the well-known drawbacks recapitulated by Mr. Clothier, the reason being its great simplicity. It may, however, be pointed out that the fusible cut-out is not alone in the possibility of being tampered with; the protective devices of oil circuit-breakers can be rendered ineffective, and cases are known where the heating elements in thermal overloads have been short-circuited.

It is not, of course, necessary to employ remote-control gear in order to get improved protection in comparison to that obtained from the simple drum-type switch and fuse. There are, as indicated in the paper, any number of intermediate arrangements possible between these two extremes. We agree that the advantages of the oil circuit-breaker cannot be overlooked, but Mr. Clothier's remarks, particularly in his reference to short-circuit stresses, are really more applicable to distribution switchgear further outbye than to the actual control gear at the gate-end. The latter is designed primarily to control the conveyor motor and does not need to have the same rupturing capacity as the distribution gear behind it and on which it is entitled to depend in case of severe short-circuit. We share Mr. Clothier's satisfaction in the increasing popularity of the British Standard plug, and agree very completely with his concluding remarks.

In reply to Mr. Grover, the requirement of B.S.S. No. 270 relative to the terminal box being external to the flameproof enclosure is a very natural one and is merely another way of saying that the flameproof enclosure must be external to the terminal box; that is, flameproofness must not be dependent on the terminal box. The construction specified in B.S.S. No. 270 presents no difficulty and is incorporated in all motors purporting to meet the specification. In reply to Mr. Grover's question as to how compliance with B.S.S. No. 290 is achieved, we need do no more than suggest that there is no difficulty in designing and constructing enclosures to withstand very much higher stresses than

those specified in B.S.S. Nos. 126 and 127. Remote-control gear of the general type shown diagrammatically in Fig. 8 has been constructed with fabricated steel enclosures tested at the manufacturers' works at 150 lb. per sq. in. hydraulic pressure, and for flameproofness at the Mines Department's Testing Station at Buxton; also standard cast-iron enclosures similar to those employed for the simple drum-type switch and fuse mentioned in the paper have been tested hydraulically to destruction at a pressure of 200 lb. per sq. in.

Mr. Grover's remarks on leakage protection are interesting as being in effect a reply to Mr. Mann, and by comparison therewith fully bear out Mr. Clothier's concluding remarks concerning diversity of opinion.

The question of working to a British Standard specification is again raised by Mr. Bentley, and also Mr. Gogan. B.S.S. Nos. 168 and 270 deal with machines with Class A insulation only. If a higher heat-resisting insulation, for instance Class B, is used (which we take it is what Mr. Bentley means in his remarks), the temperature-rise can be fixed at a higher figure, but there is no British Standard specification dealing with this temperature-rise or with the ratings of the machine.

The performance of the motors as designed at present is on the whole so satisfactory that it is quite unnecessary to consider the introduction of any complication such as the Ward-Leonard or some similar system. Slipping clutches have often been tried, but their use is open to the objection that they are easily tampered with. As soon as the operator's output is restricted by the clutch slipping, he tightens it up and either the clutch does not slip, and is therefore useless for the purpose for which it was intended, or it goes on slipping at excessive overload and rapidly deteriorates. The length to which any safety device is liable to be tampered with in a colliery is well exemplified by Mr. Cooper's remarks.

Mr. Yuille's questions as to fluid transmission of power were very adequately answered in Mr. Sam Mavor's remarks.

Prof. Parker Smith and Dr. Say raise the question of drop of voltage. In some cases this is certainly fairly serious, but if a motor is designed with a sufficiently large normal starting torque it is found in practice that it can still function quite satisfactorily with very considerable drop in the line.

Mr. Bishop asks whether conveyor belts suffer from the rapid acceleration due to starting the motor by direct switching. The belts have not been found to suffer from this cause unless they are inadequate for the load. This is partly due to the fact that the belt speeds of conveyors are very low, generally only from 100 to 200 ft. per min., and also to the fact that considerable flywheel effect can be introduced in the gear-wheels, so that the jerk at starting is considerably reduced before reaching the belt.

COMMERCIAL COOKING BY ELECTRICITY.

By T. SETTLE, Ph.D., Member.

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SUMMARY.

The development and advantages of commercial cooking by electricity are set out in detail, and particulars are given of the types of apparatus used in this country and abroad.

Representative installations in establishments of different characters are described, and the effect of the commercial cooking load on central stations in various countries is discussed.

The term "commercial cooking" may be taken to apply to all cooking operations catering for a larger number of persons than is usually found in a domestic establishment.

The ground to be covered, therefore, includes complete electric kitchens, and also installations where special cooking operations are carried out on a commercial scale for the purpose of supplying certain specialities to a considerable number of customers, e.g. such installations as luncheon counters, grill rooms, and, particularly in this country, fried-fish shops.

For the correct working of any organization of a reasonable size the kitchen is essential. This condition applies to welfare installations such as hospitals, educational establishments, workhouses, prisons, and asylums; further, to factories and large business houses; and, finally, to pure catering establishments such as boarding houses, hotels, restaurants, and passenger ships. Quite recently, electric cooking has also been introduced on railway trains. Generally speaking, the above condition applies to all organizations where a large number of people have to be supplied with food once or more during the day. Obviously, kitchens of this type have to be equipped in the most modern way.

The use of electricity for kitchen equipment developed in the normal way. Lighting came first, motor-driven mechanical appliances next, and cooking last. It was difficult to persuade users that electric cooking was competitive, and the progress of commercial electric cooking was bound up with the reduction of rates for electric current. During the last few years very considerable advances have been made.

It would seem superfluous to-day to point out the advantages of electric cooking, but in order to give a complete review of the subject it may not be inappropriate to draw attention to certain well-known facts.

The principal advantages of the use of electricity for large cooking operations are cleanliness, speed, and economy.

The cleanliness of electric kitchen equipment is obvious, because there is no storage or moving of fuel and residue, no lighting of fires, no cleaning of grates and chimneys, no fumes or soot, and no evil-smelling gases or combustion products which may find their way into the atmosphere. This means that the rooms and apparatus remain perfectly clean, and the health of the kitchen staff is much improved, which can easily be confirmed by anyone running a large electric kitchen.

The speed of service is bound up with the nature of the electrical equipment. Whilst the heating-up and maintenance of boilers or coal fires take a considerable time, electrical equipment requires only the handling of a few switches in order to make everything ready for working.

One of the principal points of economy is that electric heat acts direct on the food materials, and nearly the whole of the electrical energy supplied is used for heating the food. Furthermore, all electrical apparatus is properly lagged, so that heat losses by radiation can be ignored. This means that the efficiency compares very favourably with that of fuel-fired apparatus.

With the latter, exact calculation of the quantity of fuel required for each process is impossible, but with electric heating it is fairly easy, because, as soon as a switch is turned off, the supply of heat ceases. At the same time the residual heat can be used to advantage.

With no other form of heating can regularity be so easily maintained. Once the correct degree of heat is obtained the supply is always constant, and it can be distributed uniformly over a large surface. The food is of regular quality, more tasty, and more easily digested.

It has been definitely established that, owing to reduced shrinkage, a saving of up to 10 per cent can be obtained when roasting meat. The reasons for the smaller shrinkage are principally the more easily adjustable temperature-control of the electric oven, the absence of any necessity for opening the oven door, and the steam-tight construction of the electric oven as compared with fuel ovens, which latter are designed to circulate the combustion gases about the food.

It has been proved in various countries that the saving when roasting meat in large establishments more than fully covers the cost of the electricity used. There is also a considerable saving in fat, because food can mostly be prepared in its own juices.

There is also, generally speaking, a saving in floor space when electrical apparatus is installed, there is a lower maintenance cost as compared with fuel- or even with gas-fired apparatus, and the fire risk is reduced to a minimum.

The selection of suitable apparatus depends entirely upon the purpose of the kitchen. The demands, for instance, for a works canteen are entirely different from those for an hotel or a large restaurant, but in every case the number of people to be catered for is the principal consideration.

In laying out electric kitchens certain advantages of electric cooking have to be borne in mind, such as the elimination of storage for fuel and ashes, and the elimination of brickwork, flues, chimneys, and other accessories necessary when coal or gas is being used.

The electrical installation has to be carefully designed. A main switchboard and distribution board are desirable, and all wiring must be easily accessible and laid in such a manner that flooding during cleansing operations is avoided.

For larger kitchens it is advisable to have a pilot-light indicator board, so that the supervisor can see at a glance which apparatus is in use.

The use of electric heating for heavy-duty or commercial cooking equipment is perhaps not so far advanced or general in Great Britain as it is in various parts of the Continent and the United States, yet, from inquiries made, it would appear that the question of heavy-duty installations was probably first tackled in Great Britain. The earliest record of such an installation is that of Messrs. Pimm Brothers in Dublin, who put in an equipment containing roasting-ovens, fish-fryers, vegetable-boilers, etc., in 1907 or 1908. This was to cater for their staff of 350–400 people, and was in constant use until 1929, when their staff ceased to live in. This is not a bad record for an early effort.

The earliest development on the Continent took place in Switzerland, very likely owing to the general use of water power for generating electricity. The early realization there that electric cooking on a large scale, with the possibility of cheap electric supply, offered so many advantages over other forms of heating, led to very rapid advances being made. The author believes that the earliest efforts were in connection with bread-baking, and general installations followed very quickly.

Developments in Germany came later, but very rapid progress has taken place during the last few years.

France is beginning to become interested, and other countries on the Continent will no doubt follow.

The author has no information with regard to Sweden and Norway, where water power is also available, but a few years ago inquiries made in Stockholm failed to provide any information with regard to large cooking installations.

After the early installation referred to above, progress in Great Britain was rather slow. About 1910–11, however, a start was made and some large installations were connected up, one of the first being Messrs. Debenham and Freebody's original equipment.

The introduction of nichrome wire in place of eureka and other older resistance wires greatly assisted the development of heavy cooking apparatus. As this wire was in general use in the United States some time before it was available over here, American manufacturers were able to make big strides forward, whilst we in this country were still struggling with the various types of black-heat resistance wires which were then available.

The Electrical Exhibition of 1911 helped matters forward, and some progress was made between that date and 1914. During the War, surprising as it may seem, quite a number of cooking equipments were connected up in munition factories, aerodromes, hospitals, etc. Real progress, however, as far as this country is concerned, only dates from 1920–21, and to-day heavy-duty electric cooking is everywhere a thoroughly established fact.

It is most noticeable that by far the larger proportion of heavy-duty cooking equipment is installed in works canteens, institutions, hospitals, and similar classes of premises. Several factors account for this. In this kind of establishment or, generally speaking, in public institutions, the decision as to the use of electricity is not left to the chef and kitchen staff, as is very often the case in restaurants and hotels. It is usually dealt with by the engineering staff and the management. Very often the supply of electricity is taken in bulk for power purposes, and a few thousand units more or less for cooking purposes would not affect materially the cost of the supply.

In most works canteens the cooks are women, who are not so much imbued with old-fashioned ideas as the average chef. Naturally, also, the nature of the meals to be prepared, which are far simpler and are not left so much to the discretion of the people who have to eat the food, has something to do with this more rapid development. It is obviously easier to prepare stereotyped meals for a canteen, school, hospital, or other similar institution, than to cater for the very varied demands and tastes which are met with even in small restaurants and hotels, and certainly in the larger establishments of this type.

As far as the attitude of the chefs and hotel or restaurant cooks is concerned, they are very reluctant to alter in the slightest degree their established ways of cooking. They want apparatus designed to suit their methods, and they are not prepared to alter their methods to suit more modern apparatus which may have to be used in a different way from that to which they have been accustomed, possibly for some generations in the same family. This attitude of the chefs is met with much more in England than on the Continent—with the exception of France—or in America. In Switzerland, Germany, and the United States, the cooking fraternity is much more open-minded and progressive, and this attitude has done much to assist in the general advance that has been made.

In developing electric cooking apparatus it has been necessary to scrap some old-fashioned ideas and put forward some altogether new designs, just in the same way as the steps forward from the old-time wood-fire to the coal-range, from the coal-range to the gas cooker, and thence to the present-day electric cooking appliances, each in their turn necessitated the scrapping of ideas held sacred by the cooks of the period.

Electric cooking equipment ought to be designed specially for electricity and should not be a fuel-fired or gas-fired appliance adapted to use electricity. It is quite true that to a large extent the development took place on these lines, but improvements in design have recently been made, and we can speak to-day of real heavy-duty electric cooking apparatus.

The principal feature which enabled designers to construct an entirely different type of apparatus is the entire absence of the products of combustion.

With properly-designed electric cooking equipment

much more can be done than has hitherto been possible, and the comparative ease with which electricity enables just the required amount of heat to be applied where and when it is wanted is impossible with other methods.

The kitchen staff must also be taken into consideration when laying out an electric kitchen.

In a works canteen kitchen, where usually one or two women cooks are employed, the type of complete range with boiling-plates mounted over the roasting-ovens may be used, because under such circumstances it is possible that one cook only will attend to the roasting of meats in the ovens as well as the receptacles for cooking on the hob. On the other hand, where a number of different cooks are employed who carry out various operations in the kitchen, differently constructed types of apparatus must be used, with separate roasting-ovens for special cooks to look after, whilst vegetable boiling, preparation of sauces, etc., are carried out under the control of the cook directly responsible for that class of work.

The use of electricity allows of the easy separation of apparatus in this way, and thereby results in far greater flexibility and efficiency in the working of the modern kitchen.

In selecting the necessary apparatus for large kitchen equipment, local circumstances have to be taken largely into consideration. Where, for instance, steam is available for manufacturing or other purposes, it would not be advisable to put forward appliances in which steam would have to be generated by electricity, such as steamers, soup-boilers, large vegetable-boilers, etc. All these appliances can be heated electrically and are giving satisfactory service, but the cost of generating steam electrically would probably exceed that of the available steam.

Types of Apparatus.

Generally speaking, the following types of apparatus are universally used, although the construction varies to some extent in different countries. There are, in addition, some appliances, referred to later on, which are peculiar to certain countries.

Roasting-ovens; cabinet roasting-ovens; complete ranges, comprising one, two, or more roasting-ovens with a hob-table carrying various numbers of boiling-plates (sometimes also a grill); boiling-tables; hot-cupboards (often fitted with carving-wells and covers); bains-marie (sometimes embodied in hot-cupboards); pastry-ovens; bread-baking ovens; fish-fryers; toasters and grills; steaming-ovens; stock-pots; soup-boilers; vegetable-boilers; urns; water-boilers; coffee-percolators; storage water-heaters.

The electrical equipment for all these appliances is composed of heating-elements, which may differ according to the type of apparatus, the necessary wiring, switches, and fuses. The two last-mentioned are sometimes mounted on the appliance itself, although the practice varies in different countries. Especially for larger appliances, separate control-boards are fitted carrying switches, fuses, pilot lamps, and other electrical accessories.

The author does not consider it to be within the scope of this paper to give details of the mechanical construction of the various apparatus, although some salient features may be referred to when the appliances are dealt with in detail.

For the internal wiring of practically all appliances, it is the practice in this country to use bare wires wherever possible. Beaded wires are fitted in some cases, but, generally speaking, the author does not recommend this practice. In America, special impregnated asbestos-covered wire is mostly used. It has to be borne in mind that, in the case of many of the appliances, wires have to be brought through lagging, and care has to be taken to avoid any chemical effect of the lagging material on the wiring material.

Roasting-Ovens.—These are made in various sizes. For smaller installations, and particularly where roasting-ovens form part of a complete range which carries also the necessary boiling equipment, the well-known normal type of roasting-ovens of various sizes can be used, either singly or in multiples.

The average electric loading depends on the cubic capacity, which would be in this country, for ovens of about 7 000–8 000 cubic inches, at the rate of 0·5-watt per cubic inch. It is found that as the capacity of the ovens increases, so, *pro rata*, the loading per cubic inch tends to decrease.

The position and type of the heating elements in roasting-ovens vary in different countries and with different manufacturers. No particular system appears to be preferred.

In Great Britain we have mostly side-mounted elements, but top and bottom elements are used by some manufacturers, and in some cases both side and top and side and bottom. Much can be said for both of these systems, but, generally speaking, side elements are found to be acceptable.

In Switzerland, Germany, and the United States, top and bottom elements are mostly in use, but this may be due to the fact that whilst in Great Britain the doors of roasting-ovens are mostly arranged for side opening, in the countries referred to drop-down doors are generally fitted.

The average loading of roasting-ovens in Germany is 0·7 to 0·5 and in America 0·6–0·4 watt per cubic inch.

The elements themselves are composed of nichrome spirals usually fitted on refractory panels, but in some cases mounted on porcelain insulators or cleats or wound on mica strips.

The lining of the ovens is worth mentioning, as black steel is sometimes used. Mostly, however, vitreous enamelled surfaces are preferred, and recently monel metal has come into use.

The oven elements are usually arranged for series-parallel 3-heat control. They must be properly protected from splashes by splash-guards. Connections must be arranged in such a way that the elements can be removed easily in case an exchange becomes necessary. Quite recently, both here and abroad, efforts have been made to use elements of the plug-in type, but plugs and sockets are likely to give trouble with heavy demand.

With regard to American ranges, it is to be noted that they are usually built up from single units, each comprising a roasting-oven, the necessary control equipment, and hob equipment.

Cabinet Roasting-Ovens.—These are usually installed in this country where larger roasting operations are carried out; they are simply roasting-ovens very much on the lines of the smaller ovens, but of much heavier construction.

On the Continent and in the United States, there are used for large roasting operations ovens which are more like the type of bread-baking ovens in use in this country and abroad.

Complete Ranges.—These consist of one or more roasting compartments and a hob carrying various numbers of boiling-plates and also, as far as this country is concerned, a grill, which varies in size according to the available space. These boiling-plates are one of the most important items in electric cooking; they are still the weak point of heavy-duty electric cooking equipment and the one which causes most trouble with the personnel of the kitchen.

The main duty of the engineer responsible for the design and construction of electric boiling equipment is to give at the same time rapid heating, high efficiency, and long life. It is sometimes very difficult to combine these three requirements.

The development of hot-plates for heavy-duty apparatus followed very much on the lines of the boiling-plates used for domestic purposes. A few years ago open-coil boiling-plates were used practically exclusively. They gave rapid heating and also good efficiency, but their life was dependent upon the avoidance of spilling, boiling-over, or similar mishaps.

At the present time the open-coil boiling-plate has gone out of use almost entirely, and enclosed hot-plates of various types are now the general practice.

The older types of hot-plates consisted of cast-iron tops fitted with elements of the clamp type. The possible loading of these hot-plates, particularly of the larger sizes, was severely limited. Now in practically all countries hot-plates of the embedded type are the general practice.

The expression "embedded type" defines a construction which consists of a cast-iron top provided on its under side with grooves containing the coils of resistance wire. These coils are embedded in refractory mixtures of various compositions, and the entire plate is then baked at a temperature which may vary according to the composition of the refractory. This practice applies to practically all British and Continental hot-plates, although hot-plates of other constructions are still in use.

Considerable attention is being given all over the world to improvements in the design of the heavy-duty hot-plate, and the author thinks that the next few years may see considerable changes.

Manufacturers in this country are continually pressed by users to reduce the heating-up time of hot-plates by increasing the number of watts per square inch, and in many cases the danger point has been passed in trying to meet the wishes of the consumers; with the result that hot-plates under heavy-duty use do not have a reasonable life. The author thinks that a reasonable loading is from 28 to 30 watts per square inch. He is not aware of any hot-plate of the modern embedded type in this country larger than 12 in. × 8 in., but bigger surfaces, of course, can be built up by using smaller units.

For restaurant cooking, a fairly large surface has to be maintained at a high temperature, and at the same time the hot-plate must have a long life in spite of the rather rough usage to which it may be subjected and the fact that it may often be left on at full heat for hours without any utensil standing on it. This, of course, must lead to premature breakdown.

Naturally, chefs would like to have as large a boiling-plate as possible in the available area, so that they can use pots and pans of all sizes and slide them about as they wish during cooking operations.

With rectangular plates it is a simple matter to build up large boiling-plates, but with large circular plates this cannot be done. At the same time it is known that pots and pans are usually circular, and if each pot could have its own boiling-plate the use of circular plates might be ideal.

A combination of square (or rectangular) and circular boiling-plates is very much favoured by certain chefs, but from a manufacturing point of view it must be realized that to cater for everybody's wishes and tastes increases the cost and, if insisted upon, makes electric cooking equipment non-competitive.

In the United States, hot-plates are so arranged that they practically cover the entire surface of the hob. The usual commercial units are 12 in. × 18 in., loaded to 4 or 5 kW, and 9 in. × 24 in., loaded to 4 kW. This means 19–23 watts per square inch.

The general practice in the United States is to use hot-plates containing elements of the "Calrod" type, which is a special construction evolved by the General Electric Co. of America. The coils of resistance wire are drawn into a metallic tube and embedded in magnesium oxide. These tubes are then heated and swaged, whereby the resistance wire is firmly embedded in the magnesium oxide. The tubes can then be bent into any suitable shape and cast into cast-iron tops forming hot-plates. It may be interesting to note that elements of this construction are also being used for ovens and other cooking equipment. Elements of this type have quite recently been manufactured in this country.

Circular hot-plates for heavy-duty apparatus are not used in the United States, but in Germany and Switzerland they are often employed either exclusively or in combination with rectangular and square plates. The following are the average sizes and loadings:—

Switzerland.

400-mm diameter, loaded to 4 kW, i.e. 20·5 watts per sq. in.

470 mm × 470 mm, loaded to 4 kW, i.e. 11·6 watts per sq. in.

Germany.

(1) 220-mm diameter, 1·5 kW, i.e. 25·5 watts per sq. in.

(2) 300-mm diameter, 2·5 kW, i.e. 22·7 watts per sq in.

(3) 400-mm diameter, 3·5 kW, i.e. 17·9 watts per sq. in.

The larger German hot-plates are:—

650 mm × 650 mm, loaded to 9 kW,
600 mm × 700 mm, loaded to 11 kW,

i.e. 13·8 and 16·9 watts per sq. in. respectively.

These latter, square or rectangular, plates are recommended for very heavy work.

The case referred to previously, where roasting and other cooking operations are carried out by different members of the kitchen staff, led to the design of boiling-tables.

Boiling-Tables.—These are practically the hob of a complete range, removed and put on a separate stand, except that a grill is never fitted.

Boiling-tables, as we know them here, are not used in other countries. In Switzerland, Germany, and the United States, if separate boiling equipment is installed it is usually combined with warming-cupboards or store cupboards. In America these appliances are marketed under the name of "cooking-tops."

In this country, however, if anything is combined with a warming-cupboard it is usually carving-wells with cover, and sometimes bains-marie. The latter are, in Germany and Switzerland, very often embodied in the cooking range.

There is no need to go into the details of warming-cupboards and bains-marie, as their construction, both mechanical and electrical, is simple and well known.

Pastry-Ovens.—These are very important apparatus in a large kitchen, and in most countries are on similar lines and of the same type and appearance. The loadings vary according to the type of establishment in which they are installed, and to a large extent any variations must be left to the individual ideas of the pastrycooks and to the practice in different establishments and countries.

The temperature at which pastry is baked is usually considerably higher than the ordinary roasting temperature of meat, and therefore the loading is usually about 0·7 watt per cubic inch.

Bread-Baking Ovens.—These also form an important part of the equipment of a large, up-to-date kitchen.

For use in conjunction with electric kitchens, baking-ovens of the Peel type are installed.

Fish-Fryers.—In Germany and Switzerland, where much less frying is done than in English-speaking countries, this operation is probably usually carried out in deep pans on boiling-plates.

In the United States and in this country, however, special apparatus has been designed for the purpose.

The British equipment usually consists of suitable pans heated from underneath, the elements being either attached to the pan itself, which interferes very much with removal and cleaning, or fitted entirely separate from the frying-pan, which is the more recent tendency. According to the size of the installation the necessary accessories, such as draining-racks, provision for emptying the fat, etc., have to be provided.

The loading for these fish-fryers is fairly high, because the cooling-down of the hot fat by the sudden immersion of the material to be fried has to be taken into account. In British fish-fryers the loading is usually 2·5–3 watts per cubic inch of pan.

In the United States special apparatus has been designed, which is marketed under the name "fry-kettles." They are of a very elaborate construction and are fitted with thermostatic control, and it is to be noted that the depth of all classes of the so-called "deep fat-fryers" is considerably greater in the U.S.A. than either here or on the Continent. This apparatus is used perhaps more for doughnuts than for the frying of fish and chips, doughnuts being almost a national food in the United States.

In this country, considerable advances have recently taken place in the design and supply of very large ornamental fish-frying ranges for installation in fried-fish shops. Particularly in Lancashire and Yorkshire this kind of apparatus is becoming popular, and the author does not know of any similar apparatus in any other country.

These fish-frying ranges are usually a combination of a number of fish-frying pans mounted on an ornamental stand, sometimes provided with pictures and mirrors on tiled grounds.

In many cases these ranges are not specially designed for electric heating, and the framework can be used equally well for gas or oil heating.

Grills.—The electric grill and also the gas-heated grill differ from the old-fashioned coke or charcoal grill because the source of heat has to be above and not below the meat to be grilled. This means a reversal of the usual practice, and in many cases chefs object to it.

Various efforts have been made, e.g. globar rods, to mount the heating elements below the meat and either protect them suitably or use material which would not be affected by fat dropping on it, but these efforts have not met with great success. There is not, however, any reason why, with proper handling, satisfactory results should not be obtained with the elements mounted above the food to be grilled; and all the large establishments which have made a practice of electric grilling produce chops and steaks of at least as good a quality as with coal or gas.

Some very large electric grills installed in this country have been fitted with hot-cupboards in addition to the usual grilling surface. Thanks to the use of electricity and the fact that the heating elements are mounted above the meat, all the fat dropping off can be collected in a fat drawer specially provided for that purpose at the bottom of the grill. The value of the fat thus collected amounts to a considerable sum, and the author knows that in one particular case it practically paid for the current used.

Grills are used in all countries. They are of very similar pattern and construction, except that the design of the elements varies. In some cases china-panel elements are used, in other cases coils are mounted on cleats.

In America, grills are called "broilers," and are extensively used in a great variety of establishments. The loadings are:—

England : 20–22 watts per sq. in. of grilling surface.
Germany: 20–22 watts per sq. in. of grilling surface.
U.S.A. : 18–20 watts per sq. in. of grilling surface.

Other appliances.—The author does not propose to go

into the details of steaming-ovens, stock-pots, soup-boilers, vegetable-boilers, urns, and water-boilers, as the construction and use of these appliances are very well known.

In Germany and Switzerland very large boilers arranged for tilting are installed. They are used principally for soup and vegetables, and can be tilted either by hand or, in the larger sizes, by worm gear. They are either equipped with direct side and bottom heat, or heated through a water or oil jacket.

Appliances peculiar to the United States are waffle-irons, griddle-plates, sandwich-toasters, egg-boilers, and the fry-kettles already mentioned. Such apparatus is used in very large numbers as pantry and counter equipment for quick-lunch bars, railway buffets, cafeterias, etc., where electrically cooked food of a limited variety is supplied for rapid consumption.

Quite recently, counter equipment, consisting particularly of sandwich-toasters, waffle-irons, and similar appliances, is being introduced into this country, principally by American firms, but, in view of the increasing demand, British-made articles of this type will soon be available.

An important accessory for any place where commercial cooking operations are carried out is a storage water-heater, which provides at any time water at 180° F. for cooking and washing-up operations. Incidentally, these water-heaters provide a very satisfactory load and diversity factor for central stations.

Marine Cooking Equipment.

An undisputed testimonial to the reliability of present-day heavy-duty electric cooking appliances can be found in their ever-increasing use in the galleys of ocean-going passenger boats, as well as on board the warships of the different navies of the world.

Ship's galley equipment has to be built on somewhat different lines from the usual shore apparatus. The rougher treatment which it has to withstand necessitates the use of heavier-gauge metals, etc., whilst the restricted space usually allowed for a ship's galley calls for a more compact design than is usual. First and last, however, robustness of construction throughout must always be the keynote of manufacture. For example, in connection with certain naval contracts for cooking equipment, one clause states that the apparatus must be capable of withstanding continually the shock of heavy gunfire, without any portion moving, becoming loose, or breaking. Each piece of equipment must be so constructed that any wearing parts, elements, switches, fuses, etc., can be instantly replaced.

On board ship as well as on shore, it is usual to employ, where possible, a certain amount of steam cooking, the necessary steam being supplied from the ship's own boilers.

Main galley ranges usually comprise ovens and boiling-plates, only the grillers being separate units. The oven doors are always of the drop-down pattern, with short, swinging legs which rest on the deck when the door is open, thus forming a platform on which tins of meat can be rested. These swinging legs must be of uneven length to allow for the camber of the deck.

The range hob-tables are fitted with fiddle bars, so that saucepans, etc., will not slide off in rough weather. A protecting hand-rail is also fitted round the edge of the hob-table to prevent the cooks from coming into contact with the heated top.

Similarly, hot-presses (hot-cupboards) with carving-table tops are also fitted with protecting rails, while any covers over carving-wells must be so fitted that when in the raised position they do not swing about with the motion of the ship.

In the hot-cupboards, all plates which are being warmed are housed in suitable plate-creels to prevent them from sliding about and getting broken or chipped.

Urns and water-boilers are fitted inside with splash-baffles, and every precaution has to be taken to make everything perfectly safe and satisfactory in use.

Electric Cooking on Railway Trains.

It may be of interest to refer to electric cooking installations on railway trains, of which a number have been put in use in this country during the last few years.

The advantages of cooking by electricity in a railway train are obvious. The principal one is that the kitchen staff are able to do their work in a cool and pure atmosphere.

The electric cooking equipment on a railway train is usually placed in a separate kitchen car. In the kitchen proper, all the cooking equipment is mounted at one end, which leaves the remaining space for ordinary kitchen work, the food being passed out through serving windows into the corridor.

The equipment usually consists of a cooking-range, which is a composite unit embodying a roasting-oven, with a steaming-oven, a grill, and a hot-water tank mounted above, and a boiling-range with hot-plates for frying, boiling, etc., and a vegetable-boiler of comparatively large capacity. A hot-cupboard is also fitted for heating the plates and dishes required for the service. Arrangements are made for an adequate supply of hot water for cooking and washing-up.

The electrical energy for operating the cooking apparatus while the train is under way is provided by dynamos carried on the under frame of the kitchen car, supplemented by a battery of accumulators to enable cooking operations to be continuous during intermediate stops.

The dynamos are each of 7·2- to 10-kW capacity, with self-contained automatic pole-changers, and they are belt-driven from the axle of the carriage. The machines are connected to the battery and cooking equipment by automatic switchgear, which functions as soon as the dynamos are running at the proper speed, and is disconnected when this speed is not maintained. The usual safety devices are installed for protecting the battery.

Each cell contains from 15 to 19 plates fitted in ebonite boxes with sealed-down lids. The battery usually comprises 90 cells, three cells in a crate, and they are arranged in two boxes on the under frame.

The wiring is carried in enamelled, screwed conduits, which are earthed, as also are the frames or casings of the cooking apparatus.

Representative Installations.

It may be of interest to give some details of actual equipment installed, with particulars of the class of work done.

Restaurant.—In one large public restaurant in London, where the catering is on good-class lines, the equipment was designed to provide about 5 000 meals per day. Such meals would mostly be *à la carte*, with a fair amount of grilling work. The equipment includes:—

One cabinet roaster (51 480 cub. in.).
One 4-oven island range (12 960 cub. in. per oven).
Four grillers (each 864 sq. in. of grill surface).
Five boiling-tables (7 000 sq. in. of plate surface).
Three steaming-ovens (each 17 280 cub. in.).
Four plain hot-cupboards (each 6 ft. × 3 ft. × 2 ft. 9 in.).
One hot-cupboard and carving-table (16 ft. long).
One hot-cupboard and carving-table (12 ft. long).
Two 20-gallon stock-pots.
Three separate bains-marie.
One fish-frying outfit.
Two 2-deck pastry-ovens.
Three half-sack baking-ovens.

The total load connected is over 450 kW.

The initial cost of this equipment was approximately £2 300. The maintenance cost amounts to approximately 2½ per cent per annum. The approximate annual consumption is 365 000 units, or 1 000 units per day.

The number of meals per day varies from 100 lunches and 300 teas up to 5 000 lunches and 12 000 teas, besides various banquets during the year. In one week last year 40 000 lunches and 65 000 teas were supplied.

West End institution.—In the kitchen of a large West End institution, where the equipment was designed to cater for about 2 000 people per day on somewhat simpler lines than the installation just described, the appliances include:—

One cabinet roasting-oven.
One bank of three roasting-ovens.
One 2-deck pastry-oven.
One 3-pan fish-fryer.
One large island-type boiling-table.
Three hot-cupboards and carving-tables.
Two bains-marie.
One double-compartment griller.
Two steaming-ovens.
Four boiling-pans, for vegetables, etc.

And in the tea-room servery there are:—

Two toasters.
Three milk urns.
Three sets of water-boilers for tea-making.
One large coffee-percolator.
One set of egg-poachers, etc.

The total load is 230 kW.

The initial cost of this installation was approximately £1 200, and the maintenance cost is slightly more than 1 per cent per annum.

1 000 meals per day, in addition to 4 000 mixed pastries, are supplied. The approximate current consumption is 138 000 units per annum, which is equivalent to approximately ½ unit per meal.

Hospital.—In a hospital in the West of England, where 120 patients are catered for daily, the electric cooking equipment includes the following:—

Main kitchen:—
One 4-oven range.
One griller-toaster.
One boiling-table.
One fish-frying outfit.
One water-boiler.

Ward kitchens:—
One small range in each.
One water-boiler.
One hot-cupboard.

This represents a total load of 120 kW.

Factory.—In the kitchen of a very large factory in the Midlands the electric cooking equipment supplies, on an average, 6 000 meals per day between 1 p.m. and 2 p.m. The equipment includes the following appliances:—

Two large roasting-ovens, cabinet type.
Two medium roasting-ovens, cabinet type.
Three small roasting-ovens, cabinet type.
Two large fish-fryers.
Two double grillers.
One small range.

This represents a total load of over 100 kW.

The roasting-ovens will cook over 1 000 lb. of roast meat, as well as other food which can be accommodated in them, while the fish-fryers produce 120 lb. of cooked fish and 100 lb. of chipped potatoes per hour.

In this installation it will be noticed that no mention is made of steaming-ovens and similar apparatus. The reason is that a plentiful supply of steam is available from the factory boiler-house, and this steam is used to carry out all cooking work which can conveniently be done by it—a very advantageous arrangement, to which attention has previously been drawn.*

American installation.—The following are the particulars of a large American installation in Chicago, with 250 kW of connected load:—

Two 12-kW, 3-deck pastry-ovens.
One proving-cupboard, automatically controlled.
One twin hot-plate.
Two electric cooking-tops.
One electric range with ovens.
Three 4-kW frying-kettles.
Two 10-kW broilers.
Two 40-gall. stock-pots.
Two 12-kW vegetable-steamers.
Three 6-gall. coffee urns.
One 10-kW double-deck roasting-oven.
One automatic toaster.
One 3-kW griddle.
One electric roll-warmer.
One 2-section waffle-baker.
One 6-kW steam-boiler.

* The average current consumption is 1 000 units per week for 25 600 meals served. Maintenance expenditure is negligible.

One egg-boiler.
Two bain-marie pans.
Four plate and food warmers.
Two special coffee-cup warmers.
One electric batch-warmer for sweets.

The average monthly consumption of this kitchen is 28 000 units, with a maximum demand of 145 kW. The large number of small appliances is to be noted.

German installation.—One of the largest kitchens in Germany, which has a total connected load of 545 kW, is equipped as follows:—

Two large cooking-ranges, fitted with 16 round hot-plates, 4 square hot-plates, and 6 roasting-ovens.
Two boiling-tables, each fitted with 8 round hot-plates, also a hot-cupboard and bain-marie.
One range fitted with 4 round boiling-plates, 2 square boiling-plates and 2 ovens.
Three boiling-tables with bain-marie.

In addition to these there are a large number of tilting boilers, referred to previously, the biggest one with a capacity of 400 litres.

The total load is 160 kW.

There are in addition:—

Two warming-tables.
Seven hot-cupboards.
Two grills.
Three storage water-heaters, each with a capacity of 2 000 litres.

Energy Consumption.

It may perhaps be interesting to give some details of the energy consumption of different types of premises using electricity for cooking:—

(1) A West End drapery establishment using electricity and steam from main boilers and supplying approximately 2 000 good-class luncheons and 2 000 teas per day, 5 days per week, i.e. approximately 500 000 of each meal per year:—
Connected load, 244 kW.
Units used, 146 000 per annum.

(2) A West End institution supplying 600 lunches and 1 200 teas daily, 5 days per week. All-electric (40 weeks per annum):—
Connected load, 100 kW.
Units used, 112 500 per annum.

(3) A West End educational establishment supplying 120 lunches and 350 teas daily. All-electric, but closed for 3 months of the year:—
Connected load, 131 kW.
Units used, 39 761 per annum.

(4) A hospital catering fully for 800 people daily. Equipment partly steam. Three meals per day are given, and all bread is baked electrically:—
Connected load, 150 kW.
Units used, 124 800 per annum.

It will be seen that the current consumption per head per meal for the above four cases is as follows:—

(1) 0·143 unit.
(2) 0·312 unit.
(3) 0·424 unit.
(4) 0·143 unit.

Therefore, where steam is used for certain work, electric cooking for the remainder can be carried out at 0·143 unit per head per meal, and where the installation is all-electric the consumption would be from 0·312 to 0·424 unit per head per meal, according to the class of meal supplied and also the quantity.

The cost of maintenance is an important consideration. It may be divided into two sections: (*a*) mechanical, and (*b*) electrical.

As far as mechanical maintenance is concerned, this will very much depend upon the treatment of the equipment by the kitchen staff. The electrical maintenance may consist of renewals of boiling-plates, elements, switches, etc. The replacement of electrical material depends very much upon the nature of the establishment, and for equipments installed in canteens, hospitals, etc., where set meals and hours are maintained the maintenance costs are very low, averaging between 1 and 1½ per cent of the cost of the equipment per annum.

For equipments installed in busy restaurant kitchens where the appliances are more or less in use for very long hours, the maintenance costs are higher, and may vary from 3 to 5 per cent of the cost of the equipment per annum. Hot-plates left on at full heat all day and doing little work may require fairly frequent replacement. This, however, can be reduced to a minimum if the kitchen staff is properly instructed and uses to the best possible advantage the 3-heat control provided.

Voltage fluctuation may have a certain influence on cost of maintenance. The author has not, however, been able to trace any definite trouble due to this cause. It is obvious that if the voltage rises abnormally the life of heating-elements will be reduced. Generally speaking, however, the elements and boiling-plates for commercial cooking equipment allow for ample margin. If failures occur, it is, of course, very difficult to trace them to a possible voltage-surge.

Bread-Baking.

It may not be out of place to refer briefly to electric baking, because in larger commercial cooking installations it is not unusual for all the bread, rolls, and confectionery to be produced either in the kitchen or in a separate baking establishment.

Since Mr. Ellerd Styles read his paper in 1928,* electric baking has developed very rapidly, not only in this country, but all over the Continent and also in the United States. Quite a number of all-electric bakeries have been installed, and the results are entirely satisfactory to bakers and consumers.

The effect of electric baking on the atmosphere in the bakery, and particularly on the health of the personnel, has become very marked, and it is a well-established

* *Journal I.E.E.*, 1928, vol. 66, p. 569.

fact that bakers who have been accustomed to working in an electric bakery will not agree to work fuel- or gas-fired ovens.

Rates for electric current available for baking have been very much reduced, and there is no doubt that progress in this direction will continue.

Attempts have been made to abolish night baking, but without results. Varying conditions exist in different districts, and the time of starting work is governed by the size of bakery and the output. Laws enforcing a specified time would cause many small bakeries to close and larger ones to double their plant and increase their accommodation for such plant. In crowded areas this would be impossible in most cases. It would probably necessitate moving to an entirely new area, at great expense and inconvenience. Opposition has therefore been met from the large and the small baker alike.

Incidentally, the author would like to point out that if the prohibition of night baking became a fact the electric baking-oven would have a great advantage over any other form. It would be quite an easy matter, by a time switch, to have the electric oven switched on before the workpeople arrived, so that they would find the oven ready and hot when it was time to begin their work. It is true that the question of the preparation of dough has to be considered, but, no doubt, arrangements would be made in that case to prepare the goods in proper time.

The author would like to draw attention to a recent occurrence which throws some light on the existing out-of-date legislation. A year or so ago it was decided to install a baking-oven in a certain district in the London County Council area. The local surveyor insisted that the oven should be mounted on a concrete base 6 in. thick extending 18 in. all round the oven. He produced his authority, and sure enough the bye-law framed over 30 years ago stated that such provision must be made for all ovens except gas-fired ones. Pressure was brought to bear on the authorities concerned, and now the bye-law also excepts electric stoves. As the bye-law naturally covered domestic cookers and commercial cooking equipment, very many supply authorities had been transgressing for a large number of years.

Supply Authorities and Commercial Cooking on a Large Scale.

The development of electric cooking on a large scale is absolutely dependent upon the supply of current at a reasonable rate. Opinions differ as to what is a reasonable rate, but it has been found in practice that commercial cooking becomes a possibility when current can be supplied at 1d. per unit or less.

The comparison of the cost of electric current with the cost of fuel is apt to be misleading, because all the savings in installation and the advantages of cleanliness and hygiene have also to be taken into consideration.

Where gas, however, is being considered, it may be assumed that with gas at 8d. per therm, electricity at 1d. per unit offers the usual advantages as compared with gas. If the price of gas is higher or that of electricity falls below 1d. per unit, the advantages are decidedly on the side of electricity in every respect.

The effect of a heavy cooking load on supply stations varies, of course, according to the nature of the demand. Nowadays, supply stations are very often prepared to give special rates, either on account of the large normal demand or because the maximum demand may coincide with the day valley of the load curves.

As far as canteens are concerned, where a definite meal is supplied at a fixed hour for a fixed number of people, one may assume that the maximum load coincides with the day valley, and a very reasonable rate ought to be quoted.

For hospitals and similar institutions a second meal has to be considered, but again the hours are regular and provision can be made accordingly by the supply authorities.

The actual catering trade, however, is in a different position, and the maximum demand and the diversity factor must vary according to the nature of the establishment. There must be a difference between small boarding-houses, simple restaurants, and large luxury hotels.

The load varies considerably in the larger establishments and it may therefore become necessary to give them a high-tension supply from a transformer station, if electric cooking becomes generally acceptable for establishments of this kind.

In building up the heavy cooking load, it would be of great assistance to consumers and manufacturers if a perfectly clear-cut system of charging for current were available. The author recently came across a system of charging for current which varied with the price of coal, plus a sliding charge per kilowatt of demand, plus a sliding charge for the number of units consumed. The local gas company only charged 7d. per therm for gas. It is obvious that a complicated method of charging must have a deterrent effect on prospective users of large cooking equipment.

In this country some supply authorities have been very helpful towards the development of commercial cooking by letting on hire to their consumers even large installations, and by undertaking the maintenance. Such an arrangement inspires the consumer with great confidence, and it is to be hoped that this policy will gain further ground.

The author is in a position to give some interesting particulars of German and American practice.

In Germany there are at present about 250 large electric kitchens. The annual consumption of each varies between 50 000 and 500 000 units, and it is interesting to note that even the smaller canteens and restaurants have very important consumptions of electricity. For instance, the canteen of a factory employing 350 men consumes annually for its kitchen between 40 000 and 50 000 units.

A restaurant with about 150 seats shows a consumption of 100 000 units, whilst large restaurants and hotels will reach 300 000 units and more.

The maximum demand of an electric kitchen will vary with the habits of each particular country. In Germany a simple canteen equipment will show a maximum load about two hours before the meal hour. In hospitals the morning load is usually heavier than the evening load. In Germany, where it is usual to have

late suppers, the evening load for restaurants and hotels often comes several hours after the peak of the evening load of the supply station.

It has been found that the consumption in Germany is as follows:—

Number of persons	Approximate units required per head per day		
	Canteens	Hospitals	Hotels
25	1·2	1·5	2·5
50	1·1	1·4	2·3
100	1·0	1·3	2·1
150	0·9	1·2	2·0
200	0·8	1·2	2·0
300	0·8	1·2	2·0
400	0·8	1·2	2·0
500	0·8	1·2	2·0

In the United States the energy consumption in hospitals and small restaurants will average 0·2 to 0·5 unit per meal. In a European hotel the average will be 0·3 to 0·75.

In the Commercial Cooking and Baking Sales Manual issued by the National Electric Light Association of the United States, some interesting data are given illustrating the importance of the heavy cooking load to supply authorities. For an hotel with 100 rooms serving an average of 9 907 meals per month, the average revenue was $6 893.53 per month, with a total cost of $57.56 for electric current for cooking and baking.

In a 400-room hotel, the net annual cost of electricity for electric cooking was $4 147.47. The average consumption per meal was 0·71 unit.

Later information from the United States is given in an article in the *Electrical World* of the 23rd May, 1931. It is stated that a survey of 24 representative electric supply companies showed that during 1930 they added 32 000 000 units from commercial cooking and baking equipment. This represents an increase of more than $700 000 in annual revenue. Whilst, in 1925, 15 representative companies had an average of less than 1 000 kW of connected load for commercial cooking, at the end of 1930 the same companies had a total of more than 50 000 kW connected, using an average of more than 1 800 units per year per kilowatt.

The power companies in the United States realize the importance of the market for commercial equipment, and they have rapidly learned to appreciate what rates are necessary in order to sell equipment and current on a sound basis.

The general opinion of American supply companies is that the load due to heavy cooking is worth having, for the following reasons:—

(1) One can expect about 1 kW of potential commercial cooking and baking load for each resident customer.
(2) The load has very favourable characteristics, and can represent 1 500 to 2 000 units per year for each kilowatt connected.
(3) It possesses an advertising value for domestic cooking.

There is no doubt that owing to the clear understanding of the potentialities of the heavy cooking load in the United States, progress during the last few years has been extremely rapid. Most of the larger supply authorities have in their employ special engineers whose sole duty it is to push commercial cooking.

In Germany, progress during the last few years has also been rapid.

In this country, however, the advance has not been so rapid as might be desirable from not only the manufacturer's, but also the supply engineer's and consumer's points of view. There are certain supply authorities who have cultivated this load and are very satisfied with the results. There are others where complicated methods of charging, such as that already mentioned, interfere seriously with progress. There seems to be a little doubt in the minds of some central station engineers as to the desirability of the load, but in every district there can be found establishments with characteristics which will allow the supply authority to obtain a load during its load-curve "valleys" and at the same time not materially increase the "peaks."

Only by the co-operation of all the interested parties can success be achieved, and if this paper can maintain and increase the interest in this kind of load, the author will be glad to have been of assistance.

In conclusion, he desires to express his thanks to his assistant, Mr. R. Hill, for help in preparing the paper, and also to the following firms who supplied information:—Jackson Electric Stove Co., Ltd., J. Stone and Co., Ltd., Westinghouse Electric International Co., Commonwealth Edison Co., Benham and Sons, Ltd.

Discussion before The Institution, 18th February, 1932.

Mr. R. S. Downe: It was 20 years ago that the supply company with which I am associated began to take an active interest in the development of cooking by electricity. At that time the electric cooking equipment available was so unsuitable that we took what was for a supply company the somewhat advanced step of trying to make such equipment ourselves. We were not exactly manufacturers, but we assembled domestic and commercial cooking equipment. In order to widen our experience we decided to open a restaurant, and to build the necessary cooking equipment for it ourselves. The restaurant was run successfully from 1913 to 1926, and in that period supplied about 740 000 meals. The annual consumption was about a quarter of a million units. As a result of that experience we were able to supply a number of equipments to large institutions in this country and abroad. Some of these installations are working to-day. Amongst the multifarious uses of

electricity at the present time, heavy commercial cooking must take a very high place. It constitutes a very desirable load, in view of the fact that it is on for 7 days each week throughout the year. In connection with new buildings, there are large numbers of hotels, boarding-houses, clubs, etc., in our areas where electric cooking is not being adopted, probably (as the author suggests) because of the difficulty of overcoming the objection of the chefs. Hotel and restaurant chefs are artists who have been accustomed to producing results with certain tools, and they do not like to jeopardize those results by using tools to which they are not accustomed. It seems that we shall have to have properly trained assistants to deal with this branch of the business, and we must insist upon having standardized equipment which we can let out on hire in units. As regards the cost of energy, a ½d. per unit unrestricted cooking rate is offered by one London company, while for other companies the figure is ¾d., so that there does not appear to be any difficulty on that score.

Mr. V. C. Hardy: I recently installed an electric kitchen in the Dorchester Hotel and it has proved to be a great success. The chief difficulty encountered was that of educating the people who were going to use the kitchen, and I found that this could be done only by patience and time. I think that chefs condemn electric cooking because they believe it to be unreliable. A similar difficulty occurred when chefs were converted from coal to gas, but it was eventually overcome, and I have no doubt that the use of electricity will spread much more quickly than did the use of gas. Electricity is very desirable as a heating medium, because it is the nearest approach to coal so far as heating effect is concerned. It is useful to impress this point on chefs, who as a rule have been trained to use coal-fired cooking apparatus. This similarity between the heating effects of coal and electricity has been confirmed at the Dorchester Hotel kitchen. So far as speed is concerned, in high-class *à la carte* cookery the speed at which certain dishes have to be cooked cannot be varied, no matter whether coal, gas, or electricity is used. The great advantage of electricity for cooking these dishes is that it enables one to obtain the exact temperature required for the kind of food one is going to cook. Electricity gives better results because it is more scientific than rule-of-thumb methods. On the subject of educating the staff, it is very difficult to get them to accept the change to electric cooking stoves, because to change the methods employed in big kitchens staffed by about 80 chefs is like altering the whole system in a works. It is difficult to dogmatize about the lay-out of kitchens, because each one is designed to suit a special purpose. A kitchen such as that to which I am referring has probably to be much larger than one which caters for three or four times the number of people, all of whom are served with the same dishes at the same time. In a high-class hotel most of the dishes are cooked specially for each customer, so that a large amount of small cooking apparatus is necessary. Special large-size apparatus is also kept for catering for banquets. We have applied electricity to the announcing of orders. Formerly a kitchen clerk was employed who created a great amount of noise by shouting out the names of the dishes required, whereupon every member of the cooking staff concerned in a particular order shouted his assent. We have eliminated all this noise by installing microphones and loud-speakers in the various departments of the kitchen. So far as the type of apparatus is concerned, solidity is the most important point. The average Continental kitchen staff will break anything which is not very solidly constructed. In this connection, if the switches on cooking ranges are placed near to the top of the ovens (as shown in one of the author's slides) they are quickly broken off. They should be placed within easy reach but well away from the range, preferably overhead. Indicating lamps are useful to show whether the ovens are one-quarter, half, or full on. If only one lamp is fitted it is difficult to tell whether an oven is one-quarter or half on, and we therefore provide commutator switches and a bull's-eye arrangement giving one, two, or three lights with one lamp. We employ gas boiling-apparatus throughout, because we found that electrical boiling was too slow and the equipment apt to become damaged through water boiling over on to it. We use a lot of steam for vegetable cooking and big boiling-pans. The ordinary technical wiring difficulties have been overcome. Nickel-chromium strips are necessary instead of copper near the ranges, because of the heat. The loadings which we employ we have arrived at ourselves by experiment. When we first introduced electric ovens the chefs were apt to complain that these were insufficiently hot, but this was only because the ovens had not been switched on long enough. However, we greatly increased the loading, so as to reduce the time necessary for heating up. In the last few months we have gradually reduced the loading again without their knowing! In a big kitchen serving a restaurant where orders are given suddenly, the ovens must be at the correct temperature for cooking what is wanted right away, whether gas or electricity is used. The kitchen porters turn on the electric ovens at a certain time every day, and when they were very much overloaded they often attained too high a temperature and orders were ruined. This overloading was employed in the first instance to show the chefs what could be done, and it worked very well; but we have saved a lot of money lately by reducing the loading of the 8-kW ovens to 5 kW. We have found electric baking to be very successful. All our apparatus is British-made. We have a small oven from which we obtain the large output of from 2 000 to 3 000 rolls per day, in addition to all the usual bread. The baker has so far had no trouble with the electrical equipment. At the price at which we purchase energy, the overall running cost of the kitchen is very low. With regard to the type of apparatus, I think most chefs favour drop-down doors, which can be kicked shut with the foot. Some of the equipment shown in the author's slides was rather highly loaded, probably because rapid cooking was essential. We find that 5 kW is quite enough for an ordinary oven of medium size. Electricity is used throughout our kitchens for washing-up, ventilation, etc., in addition to cooking.

Mr. W. Ellerd-Styles: I think that a better title for the paper would have been "Heavy-Duty Cooking by Electricity." I prefer to use the word "commercial" in the sense of a "commercial proposition," rather than

to apply it to any distinct section of electric cooking. As regards the paper itself, it is stated on page 171 that "all electrical apparatus is properly lagged"; can the author give us any figures of the amount of lagging employed? Dealing with the question of shrinkage, I think he is a little conservative in his estimate of 10 per cent. My experience shows that whereas with electricity the average loss due to shrinkage is 11 per cent, with gas and coal it is 31 and 29 per cent respectively. These figures were obtained from tests with joints of beef and mutton. Turning to the question of the cost of energy, I am informed by a friend in Sweden that Stockholm has a very low cooking tariff of 0·6d. per unit from 11 to 2 p.m., and 1·2d. per unit from 2 to 11 p.m. In the provinces, however, the rate is from 0·9d. to 1·8d. per unit, which is considered to be very expensive. While the use of domestic electric cookers is on the increase, the chief obstacle in the way of development is the cost of electricity. Although this seems strange in view of the fact that a good supply of water power is available, we must bear in mind that in Sweden and other parts of Europe the bakers are accustomed to use ovens which can be heated satisfactorily by means of wood. The design of electric cooking equipment has been largely based on gas-cooker practice. There is no originality in electric cooking. For instance, the old-fashioned hinged type of door is used on electric cookers because it was originally embodied in the gas cooker. The large electric baking oven used exclusively for bread has elements placed in tubes, and these tubes are fitted inside just as in the case of the steam-pipe oven. Although this is orthodox practice, it is nevertheless wrong. For purposes of comparison let us consider three ovens of the same size (4 ft. × 4 ft.), the loading of the first being 10 kW, of the second 8 kW, and of the third 6·9 kW. These ovens will all attain the baking temperature in approximately the same time, and they also take the same time to bake a loaf of bread. The commercial user of baking ovens is solely concerned with the question of cost, and will therefore choose the 6·9-kW oven, which has the smallest consumption of the three. This shows that the loading of an electric oven is an important factor from the point of view of sales. I should be glad if the author would give further information regarding the tubular type of element, which is not placed in close contact with the material to be baked. We badly need some information as to the correct design for electrical equipment, and it seems to me that this question should have been dealt with in the paper. I should also like to know why the use of beads for insulation is not recommended. Turning to the problem of side elements versus top and bottom elements, I am in favour of bottom heat as well as side heat, and, if possible, both top and bottom heat. In connection with the design of hot-plates, would it not be advisable to break away from the orthodox and adopt something after the pattern of Prof. Parker Smith's table-pattern apparatus with plug-in utensils? Hot-plates for scones and similar commodities, of which large numbers are employed in the North of England and in Scotland, are not referred to in the paper. I should be glad of some particulars as to the loading of representative English installations. [Mr. Ellerd-Styles here exhibited some lantern slides showing representative German electric cooking equipments.] In this design of cooking range provision is made for coal heating in the event of a breakdown. All these German ranges have a guard rail round them, a very good practice not generally adopted in this country except for marine work, where it is used on account of the rolling of the ship. I do not advocate a tariff of 1d. per unit for electric baking; it makes a great difference if the price is reduced from 1d. to ¾d. or ½d. per unit. At ½d. per unit electric baking becomes a commercial proposition; at ¾d. per unit the increase in baking cost is 50 per cent, and under certain conditions I recommend electric baking and cooking at this rate, but I always advise consumers not to accept a rate above ¾d. per unit. I do not agree with the author when he states that the abolition of night baking would render electric baking advantageous in comparison with fuel-fired ovens, unless he confines this remark to brick-built thermal-storage ovens. With steel-cased ovens no advantage is secured, seeing that at least 2 hours are required in which to prepare the dough for the oven. Tests on a brick-built steam-pipe fuel-fired oven show that after 12 hours' idleness the oven temperature still remains at 400° F., and without forcing the firing it is possible to raise the temperature again to the 500° F. level required in from 55 to 60 minutes. It would be difficult for the electric oven to improve upon this. Although the author stated in 1928 that he was not in favour of thermostatic control on ovens, the following incident justifies my opinion that such control is desirable. During the Christmas holiday period a member of the staff was instructed to attend and switch on an oven so as to avoid the excessive cooling-off during 4 days' shut-down. The oven in question was fitted with a bank of pilot lights. The individual concerned inadvertently left the building without opening the switches, and 24 hours afterwards the oven had become so overheated as to cause the crown of the baking chambers to sag and touch the oven poles. It was not possible to determine the maximum temperature reached by the oven, but the glass in the light boxes ultimately resembled candle grease. The oven was ruined, the result being a loss of more than £500. Similar trouble occurred in an instance where a time-switch was fitted. Neglect to wind the clock resulted in the oven becoming overheated during a week-end, with much resultant damage. The fitting of a thermostat to limit temperature-rise would prevent such happenings. In conclusion, I should like to state that electric baking is making progress in Italy, a recent installation being an electric brick-built oven in the Vatican at Rome.

Major R. Tandy: I am sorry that the author has not said anything about the mechanical construction of the apparatus, which I consider to be very important from the maintenance point of view and also from that of first cost. The maintenance costs which he gives seem to be rather on the low side, unless they apply only to the heating elements. He does not mention switchgear, which I regard as very important. I should like some information regarding suitable types of boiling-pans for use on hot-plates. Have pans a longer life when used with electricity than when used with gas? I find that some pans take at least 25 per cent longer to boil than

others; this may, of course, be due to bad contact. In one large hotel in the North with gas cooking the maintenance of pans costs over £500 per annum, and if part of this maintenance could be saved by the use of electric hot-plates electric cooking at this hotel might become a commercial proposition. The cost per meal is, I consider, an unsatisfactory basis for comparison; a better one would be units per cost of meal, unless it were stated of what the average meal consists. The installation at Euston Station (rating approximately 200 kW) has a consumption of 1 unit per hot meal, quite a good figure in view of the fact that the apparatus is 18 years old. In all the cases quoted by the author, the number of teas far exceeds the number of lunches. I do not quite understand his remarks about bulk supply. The units used for cooking must be debited to cooking, and 1d. per unit is too high a price for energy for this purpose; something in the neighbourhood of ½d. per unit would pay commercially. The author states that the advantages of using electricity for cooking are cleanliness, speed, and economy. The first cannot be questioned, but the second and third certainly will be. He states that the loss by radiation should be ignored; if this is done, however, the kitchens will have to be heated by some other means, the cost of which must be taken into account. No mention is made of the heat-storage system of cooking on a large scale. This method will probably be strongly advocated by the supply companies of this country, owing to the constant load and low maximum demand involved. With regard to cooking on trains, the London, Midland and Scottish Railway have not yet had any of their trains equipped with electric cookers, owing chiefly to the high first cost and also to the cost of accumulators.

Mr. W. A. Gillott: I am rather disappointed at the small number of technical calculations and figures included in the paper. On page 173 the author states that for the internal wiring of cooking equipment impregnated asbestos-covered wire is used and wires are brought through the lagging: does he recommend this method of wiring? I prefer to see the wiring of cookers rigidly mounted on steatite or porcelain insulators, thus obviating the possibility of the troubles so often met with in connection with asbestos-covered wiring, and I deprecate the practice of passing the wires through the lagging. The wires should be attached to a solid terminal block, thus making a sound engineering job. Regarding the relative merits of top and bottom or side elements for roasting-ovens, the position of the elements must depend upon the shape of the oven. Those types where the width exceeds the height or depth often have the elements fitted on the back; such ovens usually have double doors. Mention is made of the use of monel metal for the oven lining, and I should like to know whether the author has had experience over an extended period of monel-metal interiors? If so, how do they behave under heavy working conditions? He states that the plug-in type of oven element is liable to give trouble under heavy-duty conditions; this, however, is entirely a question of design. I have had experience of the successful use of plug-in elements with large roasting equipment extending over a period of almost 20 years. Provided one houses the terminals in a comparatively cool position no difficulty should arise. I agree with the author as to the difficulty of making allowance for the idiosyncrasies of foreign chefs. With the extended use of large cooking equipment in kitchens this difficulty should, however, to a large extent be overcome, as the results of working under modern conditions will bring out many points of operation that will tend to provide for the personal fancies of the chef. Manufacturers may therefore find that it will not be so necessary to alter their patterns to meet so many small requests. On page 175 it is stated that pastry-ovens usually have a loading of 0·7 watt per cub. inch, but the type of pastry-oven is not mentioned. For many years I have handled and sold pastry-ovens with a maximum loading of 0·5 watt per cub. inch which have given every satisfaction as regards both cooking and maintenance results. These ovens have sheet-steel interiors. The author is probably referring here to ovens with tiled or slab bottoms, necessitating a higher loading to heat up the oven. Turning to the question of grilling, provided suitable drawers are fitted for the collection of fat the saving effected in this direction will be sufficient to pay a large proportion of the total cost of the current consumed by the installation. I have had experience with an installation catering for some 2 000 meals per day, where the value of the fat recovered from the grills was more than the cost of the electricity used per day. I am surprised to find that so little has been said regarding electric cooking on trains, for the introduction of which I was largely responsible. A paper* which I read before the Institution about 15 years ago commenced a discussion on train cooking, and I was subsequently asked to investigate the proposition. I made experiments on the (then) Great Northern Railway, and produced figures that enabled suitable battery and generating plant to be designed. The cooking equipment for some of the restaurant cars on that railway was built up on the information secured. During the tests when the gas-cooking equipment on the train was being worked at its full capacity, the temperature in the kitchen reached a maximum of 111° F. It was necessary to remain in the kitchen the whole period of the journey, as on that day three shifts of meals had to be prepared for lunch and dinner. Observations were taken every 10 minutes over the entire trip of the number of gas-jets burning, and from this the approximate consumption of gas was obtained. From the readings the number of B.Th.U. required was calculated, and this figure was used to give the necessary kW demand. The first kitchen equipment was installed a little over 10 years ago, and as a result of the experience several dining-car electric kitchens were ordered for the trains of the London and North-Eastern Railway.

Mr. J. J. McKenna: I am sorry that the author does not give more detailed information about the cost of running electric cooking equipment, especially with reference to the type of meals being cooked. To give figures of cost per meal is not very informative unless one knows exactly of what the meals consist. In large restaurants it is obvious that the cost per meal will be considerably higher than in hotels and canteens. Moreover, the paper does not deal in a sufficiently detailed way with maintenance costs. Of all electric cooking

* *Journal I.E.E.*, 1918, vol. 56, p. 102.

equipments, none are misused more than those in restaurants; the result is that as a rule the maintenance costs of such installations are fairly high. If purchasers of electric cooking equipment find that they have been misinformed by the manufacturer regarding the running and maintenance costs of the equipment, they soon spread the news to other users of cooking apparatus and in consequence great harm is done to the industry as a whole. I believe the most satisfactory results from the point of view of the customer are obtained in connection with baking ovens, where the costs are competitive and in fact very often less than those of other methods of heating. Here again I should like to see more actual figures of both maintenance (which I know is low) and baking costs. With regard to fish-fryers, while there is a large volume of potential business in this sphere for electrical appliances, considerable difficulty is encountered in the design of fish-fryers to give satisfactory service. There is the question of raising the oil quickly to a high temperature, and the loading has to be high in consequence, and also in order to maintain that temperature when large quantities of fish are put in. As a result there is a danger that in the intervals when cooking is not in progress the oil is liable to get burnt. Can the author recommend any method for overcoming this difficulty whilst still giving quick operation? His figure of 2·5 watts per cub. inch for the loading of pans is not very informative; the loading ought to be given on the basis of the square inch of heating surface because the elements are generally underneath, either clamped to the bottom of the pan or fitted separately. The loading per cubic inch conveys nothing, because the pan may be either shallow or fairly deep. Can the author give a figure for the loading per square inch?

Mr. S. J. Benham: When on a visit to America I was surprised at the small amount of electric cooking apparatus in use in that country. I should say that there is a good deal more heavy-duty electric cooking apparatus in use in London than in New York. In both New York and Chicago I was told that electric cooking, except for baking ovens, is far too expensive, owing to the high cost of current. I am surprised that the author makes such a great point of the saving in the loss of weight of meat involved by electric cooking. There is only a saving if no vent is fitted to the oven, whereas I think that for every large cabinet or other roasting oven a vent is absolutely necessary for satisfactory cooking. Ovens are often filled not only with meat but also with such things as batter puddings and potatoes, which give off a great deal of steam. If no vent is provided or the vent is too small to carry off that steam, the food is partly steamed and partly roasted; it has not the correct colour, and a good chef will not approve it. I agree with the author that where steam is available it should be used for steamers and boiling-pans, and I think it should also be used for tea and coffee apparatus, hot-cupboards, etc. Where 2 000 to 4 000 meals are required daily, it is better and more economical to put in a steam boiler and steam-cooking apparatus than to attempt to do all the cooking by means of electricity. Mr. Hardy referred to the fact that the ranges at the Dorchester Hotel have gas boiling-tops. I think that in a cooking installation for a large hotel or restaurant where many meals are served it is better to have a gas boiling-table than to attempt to use electricity for boiling purposes. This idea has been adopted in many large institutions. For instance, at the head offices of the Midland Bank, where there is a very large staff canteen, the new Princess Beatrice hospital at Fulham, and the new clinic in the Marylebone Road, London, the cabinet roasting-ovens, grillers, and fish-fryers are all electrically heated, the boiling table is gas-heated, and steam is used for other purposes. There is a good deal to be said for combining the three types of fuels in this way. It is interesting to note that in the Princess Beatrice hospital the steam is actually generated by electricity. I do not agree with the author's comparison between the costs of electricity and gas, and I regard as incorrect his statement that electricity at 1d. per unit or under will compare with gas at 8d. per therm. I think the former figure should be ½d. per unit for electric cooking. The future of electric cooking apparatus depends mainly on the cost of current, and I do not think that 1d. per unit is attractive enough. I hope that the supply companies will shortly supply current at ½d. per unit.

Mr. C. M. Flander: The author refers to electrically-operated fish-fryers, and states that, provided the tariff does not exceed 1d. per unit, the overall operating cost is competitive with that of other types of fryers. This type of equipment is in use about 5 hours per day and at a time corresponding to the daily peak of the majority of undertakings, so that from a load-factor point of view it is little better than lighting equipment, and must therefore carry its full proportion of capital charges. As the nature of the load is such that diversity cannot be taken into account, the cost of energy delivered to the low-tension system will not be less than 0·76d. per unit. As a general case it is reasonable to assume that the substation supplying the load is 10 miles from the point at which the bulk supply is received, and that the load has to be transmitted 0·5 mile over the low-tension system. For these conditions the capital charges on the transmission and distribution systems amount to 0·495d. per unit. Thus the cost—excluding management, rates, repairs, and maintenance—amounts to 1·255d. per unit. It is difficult, therefore, to see how undertakings can be expected to cater for this load at 1d. per unit. On page 179 the author states that gas at 8d. per therm is comparable with electricity at 1d. per unit, which would seem to assume (taking the efficiency of electricity to be 100 per cent) that the efficiency of gas-operated apparatus is only 27·5 per cent. It is interesting to compare this result with some recent German figures* which showed that 1 unit of electricity is at least equivalent to 15 cub. ft. of gas having a calorific value of 395 B.Th.U. per cub. ft. On the above basis this gives an efficiency for gas-operated apparatus of 58·4 per cent. These values are confirmed by some other German figures† published in 1928. I should be glad if the author would explain the considerable discrepancies between these test results and the figures he gives on page 179, and also indicate the rate of depreciation which he considers necessary for the types of equipment described in the paper.

* *Electrical Review*, 1930, vol. 106, p. 37.
† *Electrical Times*, 1928, vol. 74, p. 816.

Mr. J. I. Bernard: The author shows that commercial cooking by electricity is now being profitably employed on a considerable scale in this country and abroad. The rapid growth of the heavy cooking load in America is mentioned, but equally impressive figures could no doubt be shown by several British supply undertakings. In one district in London, for instance, there are 6 large commercial cooking installations of which the total consumption is over 1 500 000 units per annum, i.e. an average of 250 000 units each. Similarly, one municipal supply undertaking in the provinces has over 1 820 kW of commercial cooking load connected. Complicated tariffs for this class of load undoubtedly exist, but they need not in themselves prevent us from obtaining the business. The engineers responsible should be able to explain the tariff to prospective users and show what the average cost per unit is likely to be. Further facts and figures demonstrating the superiority of electricity for commercial cooking purposes could easily be given. As an example, the greater cleanliness and improved working conditions brought about by the adoption of electric heating may be illustrated by some comparative tests made in America on gas and electric roasting-ovens. It was shown that with gas firing the amount of heat required to maintain 500° F. was equivalent to 6·5 kW per sq. ft. of oven, as compared with 0·2 kW with electricity. The difference in the heat supplied in the case of an oven of 24 sq. ft. would be sufficient to raise the temperature of a normal-size kitchen (30 ft. × 40 ft. × 10 ft.) by 23 deg. F., even assuming that the air is completely changed every 3 minutes. Figures such as these illustrate in no uncertain way the great advantages which always follow the use of electricity for commercial cooking.

[The author's reply to this discussion will be found on page 188.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 29TH FEBRUARY, 1932.

Mr. R. H. Rawll: By his statement that the heating-up and maintenance of boilers or coal fires take a considerable time, the author infers that electrical equipment is ready for working directly it is switched on. This is obviously not the case so far as boiling-plates are concerned, and it would be interesting to know whether hotel proprietors, caterers, etc., consider this to be an important point, although it is admitted that once a boiling-plate is hot a small current consumption will keep it so for an indefinite period. I agree with the author that no advantage is gained by using plug-in elements, since after about a year's use the contacts often become semi-welded and corroded. I consider it unnecessary for the electrical industry to utilize for propaganda purposes the non-shrinking capabilities of electricity for roasting, since this feature seems already to be well appreciated by the public. As the author points out, the hot-plate represents the weak spot in our armour. I notice that he considers from 28 to 30 watts per sq. inch to be a reasonable loading for hot-plates in this country, and further on in the paper he gives the figure of 19 to 23 watts per sq. inch as the usual loading in the United States. Does this mean that the latter country has the more efficient hot-plate, or does it mean that users over there are content to wait longer than we are for the plate to attain its final temperature from cold? I do not agree that, in practice, current at 1d. per unit will justify electricity for commercial cooking: this figure is a trifle high. It is stated that a works canteen using electricity for cooking purposes would have a maximum load coinciding with the day valley of the supply undertaking's load-curve. Since most works shut down about midday the load drops off at this time, especially in industrial areas, but the cooking of meals to be served at this time would commence perhaps 2 hours beforehand, and it is well known that with electric cooking the greatest load is taken at the commencement of the cooking period. Switches are turned down to "low" and even "off" towards the end of the operation. It seems, therefore, that the maximum cooking load for works canteens would not coincide with the valley of the load curve at midday, but would be superimposed on the day power load a few hours previously. The paper omits to mention the induction type of cooker, where the utensil containing the food acts as the secondary of a transformer, and the induction boiling-plate, where the plate itself forms a low-voltage secondary. A great deal was expected from this type of apparatus when it was first introduced a few years ago, and in view of the ever-increasing adoption of alternating current it would be interesting to know whether the author considers that this design will be developed in the future. Can he explain why it has so far failed to find a market?

Dr. K. R. Sturley: I should be interested to know the voltage used for train cooking equipment. The paper suggests that it is 180 volts. It would appear worth while to increase the number of battery cells from 90 to 100 or 110, thus permitting the use of standard apparatus and a reduction in the current for a given heating effect. The maintenance of cooking equipment is an important factor and I feel that if this were undertaken by supply authorities generally, as in the case quoted in the paper, it would give an impetus to the sale of both large and small cookers. I agree with the author as to the need for suitable tariffs, and it is to be hoped that more supply companies will encourage a cooking load to fill in the valleys in their load curves. Thermal-storage cookers, which can store sufficient heat to allow of their being switched off during the peak-load periods, can be advantageously employed in this connection. I am not aware of the use of such apparatus in England, but it has received encouragement on the Continent. This can be partly explained by the different generating conditions prevailing abroad, where the source of power is generally water; nevertheless, the possibilities of such apparatus should not be ignored.

Mr. K. Pittaway: I should like to refer to the uses of residual heat in ovens, after the current has been switched off. On some of the slides exhibited by the author there appeared a type of roasting-oven the top of which was fitted with a boiling-plate or plates. I particularly refer to plates which are actually parts of the oven tops. If these plates were of the open-bottom

type, when being used in the ordinary way as boilers they would also heat the oven to a medium degree, and the heat so supplied to the oven could be usefully employed for purposes for which residual heat is found sufficient. The boiling-plate would thus serve the dual purpose of boiler and top element of the oven. Referring to fish-fryers, as the essential future of these units is to boil oil, have any of them been fitted with a special type of immersion heater? Is there any good reason for definitely ruling out such a method?

Mr. W. A. Gillott: It would be interesting to have a few more details of the equipments mentioned under the heading " Representative Installations " (page 177), and, if possible, a comparison of the working conditions. Taking as examples the American installation where some 250 kW of plant is installed, and the West End drapery establishment with a total connected load of 244 kW, can the author give a comparison of the maintenance costs under the following headings: boiling-plates, oven elements, grill elements, internal wiring, and switches? It would be interesting to compare the life of British with that of American appliances. If the author is unable to give details of the maintenance costs, could it be expressed as so much per thousand units consumed? Upon this basis one obtains a fair indication of the amount of work done upon the appliances. It is hardly fair to treat the maintenance cost as a percentage of the initial cost, as in some installations the equipment is embellished with nickel plating, vitreous enamelling, illuminated switchboards, and other additions, whereas in installations of exactly similar equipment not having such embellishments the initial cost is considerably lower. I particularly stress this point because when I had control of the design and equipping of national kitchens during the War, I found that the cost of the equipment was not much more than two-thirds of that of similar plant embellished for ordinary use. This also applies to the plant now used in works canteens. The author states that the maximum demand of the American installation is 145 kW with a consumption of 28 000 units per month. This is equal to approximately 2 320 units per kW of demand per annum, whereas the West End drapery kitchen averages 146 000 units per annum with a connected load of 244 kW. Can the author give a few more details of these installations? The West End plant admittedly employs a good deal of steam. Evidently water is boiled by steam, and steam is probably used in other operations. Before, however, a true comparison can be drawn between the two installations it is necessary to balance the work of each. It would be of interest if the author could show the characteristic load curve of each plant. This would not only give the nature of the demands but would also enable one to determine the diversity factors. Turning to the four installations dealt with under the heading of " Energy Consumption," I am surprised to find such a large variation in the figures of units consumed per annum per kW installed, these being 590, 1 125, 303, and 802, for installations Nos. 1, 2, 3, and 4, respectively. Can the author explain this large difference in consumption, and can he state why it is that whereas installation No. 3 records the lowest consumption per kW installed, it shows the highest current consumption per head per meal? Regarding the value of the large-kitchen load to electricity supply authorities, this business is worthy of cultivation. Apart from its revenue production, the advertising value is considerable and assists in encouraging the further use of electricity for domestic purposes. Patrons of restaurants where electricity is used for cooking will realize that it must be a commercial proposition, otherwise a restaurant would not adopt it. I agree with the author that it is desirable for the electricity supply authority to appoint a special representative who has a knowledge of the subject, to discuss kitchen problems with prospective clients. This class of work should be dealt with by men familiar with it, otherwise more harm than good may result. In discussing cooking matters with chefs and hotel or restaurant proprietors, considerable tact is necessary. If the sales representative of a supply company is not well acquainted with large-kitchen work he should confine his activities in the first instance to canteens or works kitchens, where he will discuss the matter with the engineer and thus gain valuable experience. In my opinion the United States cannot teach British engineers much about large cooking equipment; the American policy is largely one of trying a new idea merely because it is new. In the paper* on " Electrical Cooking as Applied to Large Kitchens " which I read before the Institution in 1918 I stated that some 400 kitchens with a connected load of 22 000 kW were operating in this country. Considerable expansion has taken place since then, and I should be surprised if the number of British large-scale kitchens did not now exceed the American total. Whilst I agree with the author that, for domestic cooking, gas at 8d. per therm is equivalent to electricity at 1d. per unit, this comparison is not applicable to commercial kitchens owing to the difficult nature of the work. In domestic work it is usual to carry out a culinary operation and finish it there and then, whereas in a restaurant there is often a considerable waiting-on period for both the actual cooking appliances and the hot-cupboard, urns, etc., in still rooms. In London it is the practice of a gas company to allow to hotels a special discount of approximately 25 per cent off the published charge for gas. A similar allowance is not usually made by electricity supply companies. I consider that under ordinary working conditions 8d. per therm is equivalent to $\frac{3}{4}$d. per unit, disregarding incidental savings effected by the use of electricity. It would be of interest if the author could provide load curves of the installations described in the paper. What percentage of the installed load is the average kW demand of the installations with which he is associated? I have found that where a kitchen is used for the preparation of simple meals at a definite time, e.g. for canteens, schools, etc., the kW demand averages 60 to 65 per cent of the total load installed. In kitchens catering for a varied menu such as that of a restaurant or hotel, the demand is much lower—35 to 45 per cent. This is due to the employment of special appliances for dishes that are only occasionally called for. The normal plant cannot be used for these dishes as it is usually kept running to continue the cooking of the ordinary meals.

[The author's reply to this discussion will be found on page 188.]

* *Journal I.E.E.*, 1918, vol. 56, p. 102.

SCOTTISH CENTRE, AT EDINBURGH, 22ND MARCH, 1932.

Mr. E. Seddon: I am inclined to doubt the figure of 10 per cent for the saving due to reduced shrinkage of electrically-cooked meat. I understand that the latest type of gas oven is heated externally, and I should like to know whether the results of shrinkage tests on such ovens have been compared with those on electric ovens. As regards the steam-tightness of ovens, I understand that the author has introduced a ventilator at the back of the oven instead of in the door. It is well known that steam confined in an oven which is being used for roasting spoils the condition of the food. The steam must be eliminated to permit of the food being dry-heated. Several large catering establishments in Edinburgh which use electric cooking ovens for general purposes have gas-operated boiling pans, because the electric hot-plate is found to be too slow. I therefore consider that the hot-plate should be redesigned. We have heard a great deal in recent years about machined-bottom saucepans: these are satisfactory for a time, but they gradually deteriorate. Even if their flat surfaces could be maintained in perfect condition there would remain the difficulty that the hot-plates themselves become distorted by use. The air space between the saucepan and hot-plate greatly delays the process of boiling. I believe the well type of heater with bottom and side elements will eventually prevail, and even this arrangement would be improved by a hinged, domed cover-plate to retain the heat. I agree with the author (page 172) that chefs are reluctant to alter their established practice, and I am convinced that the more general use of electric cooking is being retarded by their conservative attitude. With regard to the replacement of cooker hot-plate elements, we have changed over from the wired type to the plug-in type with complete success. When maintenance men have to use pliers and other tools for replacing elements the householder gets the impression that a big job is being undertaken, whereas a plug-in element can be dropped into position without effort and in a minimum of time. With regard to baking, 2 years ago we offered the low rate of 0·3d. per unit for this purpose between the hours of 10 p.m. and 7 a.m., but as Edinburgh bakers cannot be induced to work at night no business has resulted.

Mr. A. Mears: The question of the efficiency and adaptability of the electric hot-plate as compared with the gas-ring seems to me to be one of further research, not of combining gas and electricity in one piece of apparatus. I recently made some comparative tests of the speed and economy of a gas-ring used with an ordinary kettle, and an electric kettle loaded to 1 kW. The results indicated that for the same amount of water the cost of using the electric kettle—at the domestic heating rate applicable in Edinburgh—was a trifle less than the cost of using the gas-ring, and the two systems were equally quick. Experience of the usual type of gas-ring, placed in apparently the most suitable position for the disposal of the products of combustion, shows that the fumes of burnt gas quickly pervade the kitchen where it is in use. Has the author investigated the question of the grinding of the surfaces of hot-plates and the bottoms of kettles or cooking utensils? Unless perfect contact is made between the surface of the hot-plate and the bottom surface of the cooking utensil great difficulty is experienced in connection with the speed and reliability of the cooking operations. Referring to the question of the combined gas and electric cooker, it seems to me that a considerable fire risk is taken when such a combination is used, as a leakage to earth may readily melt the gas pipe and ignite the gas. I feel that the insurance companies would not look favourably upon this combination. According to the author electric cooking is quite economical at 1d. per unit or less; in this connection I should like to state that in Edinburgh the price averages $\frac{3}{4}$d. per unit for commercial and $\frac{5}{8}$d. for domestic cooking.

Mr. H. C. Babb: I deplore the remarks of previous speakers about the heating of water by electricity, and I support Mr. Mears's view that if electric water-heating apparatus is inefficient we ought to try to improve it by carrying out suitable research work. With regard to the cost of electric cooking, the tenants of Council houses in my area are taking up electric cooking very strongly. The cost of using a small electric cooker which we can let out on hire for 2s. 6d. per quarter, and which is capable for cooking for 3 or 4 persons, is less than that of using a gas stove in a similar house. There may be some difficulty in comparing figures obtained in this area with those of other areas, owing to the fact that a large number of the people who occupy these houses are miners and can buy coal at a cheap rate: the electric cooker is therefore probably not used quite as often as it would be in most other districts.

Mr. W. Duncan: The electrical industry is passing through a phase of development analogous to that which the gas industry experienced in its earlier days when competing with coal. The use of electricity for cooking purposes is being hindered by lack of knowledge of the apparatus, and I think it would be a good piece of propaganda for manufacturers to provide free demonstration cookers to all schools and colleges where domestic science is taught. This would enable such schools to educate the younger generation in the use of domestic electrical appliances. I am glad to know that the author approves of the embedded type of boiling plate, the introduction of which has made a great difference to progress in the use of electric cookers. I should be glad if he could indicate what the future changes in boiling-plate design are likely to be. I do not agree with the policy of certain manufacturers who make statements as to the time taken to boil specific quantities of water, as I find that the figures given are often inaccurate. For instance, these figures usually assume the initial temperature of the water to be 60° F., whereas in actual practice it averages 50° F.; this lower temperature makes a considerable difference to the boiling time. I should like to mention the case of an electrical cooking equipment in Edinburgh where all the elements

are loaded to 1·5 kW and are of the plug-in type: boiling-plate, grill, and oven elements are all interchangeable, and can be replaced in a few minutes without skilled attention. This feature should, I think, be extended and developed. The mention by the author of the case where a concrete oven base was insisted upon suggests that there might be an additional advantage in electric cooking if insurance companies could be induced to lower their tariffs to premises where cooking is done electrically. Has the author had any experience of the thermostatic control of ovens? This idea has been adopted in America even for domestic equipments. In this country we have been rather slow to introduce such refinements. The author showed a slide illustrating a battery of large electric boilers; I should like to know how the heat is applied to these.

Mr. G. Gunn: Have any tests been made of electrode boilers of the type in which the electrode can be raised out of, and lowered into, the water? Also, have any experiments been made on the high-frequency boiler?

Mr. J. Eccles: We all hear from time to time of the difficulty of regulating the boiling appliances of electric cookers; I suggest that where an a.c. supply is available this difficulty could be overcome by providing an auto-transformer with a series of tappings up and down (mostly down), so as to give a wide range of graduation on each of the three heats. If auto-transformers are as cheap as power transformers are just now, the additional cost of such a device should not be serious. At the festive seasons, when many meals are being cooked simultaneously and supply mains are being severely taxed, the auto-transformer could be used to step up the voltage slightly and thus overcome the difficulty of insufficient heat being available to cook large roasts in a reasonable time. I should be glad to have the author's views on this suggestion.

The Author's Reply to the Discussions at London, Birmingham, and Edinburgh.

Dr. T. Settle (*in reply*): Before answering in detail the various points raised in the discussions, I should like to express my thanks to the speakers for the interest shown and for their valuable contributions.

A considerable volume of criticism was directed by various speakers against the alleged failure to give details of technical and mechanical construction of heavy cooking apparatus. I can appreciate the desire of manufacturers to obtain as much information as possible with regard to details of construction used by other manufacturers. It is well known, however, that I am connected with the manufacturing side of this industry, and any particulars I might have given would naturally, in the first instance, have been particulars of the products for which I am responsible. The publication of such details might have provoked criticisms from other manufacturers, and I think it will be admitted that a discussion of this kind is entirely outside the scope of an Institution paper.

Every manufacturer has his own ideas and methods of construction. There are a few general principles which have been referred to as far as possible, but as the design and construction of heavy cooking apparatus are still in a state of continuous development I considered it advisable to refrain from dealing with matters which, in the eyes of competing manufacturers, might have been largely controversial.

Another general criticism referred to the insufficiency of information with regard to actual figures, and the particulars given were evidently not as complete as some of the speakers might have wished. It will be appreciated that I was able only to give such figures as were obtainable, and I could only give them in the form in which they were obtained, because in every single case some link would be missing which would prevent the reduction of available figures to a common comparative basis.

I welcome Mr. Downe's remark with regard to the hire of heavy cooking apparatus by supply authorities, and the necessity of having properly trained assistants in this branch of the business. Wherever such assistants are available, good progress is being made. Every manufacturer standardizes his own equipment, and under present conditions general standardization is out of the question, not only from the point of view of the manufacturer, but also from that of the user, who very often has special views and wishes.

Mr. Hardy's statement on the great success of the electric kitchen in the Dorchester Hotel is very interesting and very good news. I am glad to hear Mr. Hardy's confirmation from practical experience of my opinion of the average chef, and his suggestion as to how to deal with chefs who are averse to electric cooking is to be heartily welcomed and recommended. I fully agree with Mr. Hardy's recommendations, but there is one point on which I cannot follow him. I cannot agree with the use of gas for boiling in connection with electric roasting ovens and forming part and parcel of the complete apparatus. Modern boiling-plates are very little slower than gas boiling-rings if proper utensils are being used, and with carefully constructed apparatus damage to the hot-plates by boiling over can be practically eliminated. The speed of boiling can also be improved by the use of hot water to be made available from a storage water-heater. By introducing gas into the electric kitchen, many of the advantages of a complete electric kitchen are done away with. Apart from the vitiation of the atmosphere, the introduction of gas always brings with it the risk of explosion and fire, particularly when electricity is used on the same apparatus, and in case of any accident electricity would probably always get the blame.

I am afraid that the greater part of Mr. Ellerd-Styles's contribution to the discussion is not quite within the scope of the paper. Most of his remarks refer to my contribution to the discussion on his paper on electric baking ovens read before the Institution in 1928. The 10 per cent saving in shrinkage is an all-round figure obtainable by the average cook in an average kitchen equipment, and is not based on the results of tests carried out by experts for this particular purpose. To get absolutely comparative figures with regard to

shrinkage, tests would have to be carried out with the same kind of joint taken from the same kind of animal and roasted in electric and gas ovens of exactly the same oven capacity. It is almost impossible to obtain these conditions. Mr. Ellerd-Styles makes some very sweeping statements, which are highly controversial and very much of a commercial nature, and they ought not to remain uncontradicted. The placing of elements in tubes in baking ovens is declared to be entirely wrong. Why this should be so is not stated, but elements enclosed in tubes do not only give a longer life than other types of elements, but they also ensure better heat distribution. Comparison is made between three ovens of the same size with three different loadings (10 kW, 8 kW, and 6·9 kW), which are all supposed to attain baking temperature in the same time. This statement, if correct, means that the general construction of the ovens must of necessity be different. If the sole of an oven is brick, and in some cases the sides and back are also brick, it stands to reason that a much higher loading is necessary to attain the same temperature in a given time, than in the case of an oven having fewer or thinner tiles or none at all, but of purely metallic construction. The heat-retaining properties of ovens with thicker tiles and higher loading are superior to those of lighter construction. Once an oven has attained baking temperature it is only a matter of using the lower controls to keep the temperature at a baking level. It is, therefore, the consumption of current required for baking over a period only that counts, and whilst Mr. Ellerd-Styles mentions that a lower-rated oven may appeal more to the layman and appear to him to be a better commercial proposition, he omits to mention that in most cases heat control is available for providing full, half, and quarter heat, or full, two-thirds, and one-third heat. The all-important point for the baker is current consumption in relation to his output. If he is satisfied with this—and there may be very little difference between the various types of ovens—it is only the construction of the oven, its life, and the ease of handling which count. As mentioned above, I do not propose to deal with questions referring to details of construction.

I think that no chef would welcome the introduction of Prof. Parker Smith's table pattern apparatus in his kitchen. This type of apparatus may be useful in a private house, but it would not last long in a large all-electric kitchen.

The incident quoted by Mr. Ellerd-Styles with reference to thermostatic control has no bearing, in my opinion, on this question. Apparently through carelessness an oven was left on over the week-end. Surely thermostatic control is not intended to take care of isolated cases of this kind, but is usually meant to control the temperature when the appliance is in regular use. I still maintain that for ordinary baking operations thermostatic control is not necessary and is not used to any extent. However, in order to follow Mr. Ellerd-Styles on his own ground, I can refer to a case where an oven was inadvertently left on from Saturday evening until Monday morning, the front of the oven being then nearly white-hot. No damage was done, except to the thermometer, and the oven has since been in daily operation. This only shows that the method of construction is an important point, and isolated cases like the one quoted do not justify the extra cost of thermostats to counteract gross carelessness in working.

Major Tandy raises the question of maintenance of electric kitchen equipment. This depends very much on the method of handling. The figures given in the paper referred to heating elements and any other replacements which may become necessary. Good-class aluminium pans with bases ground dead flat are found to be quite satisfactory for use on hot-plates. Many chefs, however, prefer copper pans, but the continual cost of having these re-tinned is bound to be taken into consideration. Boiling time depends, of course, on the quality of contact between utensil and hot-plate. The expenditure of £500 per annum for utensils in a large hotel in the north with gas cooking seems extraordinarily high, and would certainly be very much lower with electric cooking. The figure of 1d. per unit for electric cooking was only given as the basis of a comparison against gas at 8d. per therm, but I quite agree with Major Tandy that ½d. per unit would put electricity for cooking on an unassailable basis. The heat-storage system for cooking on a large scale has not been developed, and I do not think it will ever be a commercial proposition unless some entirely new method can be devised. If based on constant load it would certainly be too expensive. With regard to the cost per meal, the class of meal is generally indicated by reference to the type of installation. A meal served in a canteen consists usually of a plate of meat with vegetables and a sweet. To give particulars of the class of meal as served in restaurants and hotels would be an impossible proposition.

In reply to Mr. Gillott, I certainly do not recommend that wires should be brought through the lagging, but in some cases this cannot be avoided and possible attack by the lagging material on the insulation of the wire must then be guarded against. The figures which I have given for the loading of pastry ovens refer to ovens with tiled soles. I agree with Mr. Gillott that more details of equipments and comparisons of working conditions would be valuable, but, as pointed out, this information can only be given as obtainable, and particulars of the cost of maintenance of American installations are not easily obtainable. The present method of calculating the maintenance cost by basing this on the original purchase price of the equipment is the only one which interests the consumer. The figures given are usually maximum figures, and it would be impossible to give an estimate based on a consumption of 1 000 units. It would be interesting to know this figure, but it would probably be so small as to lose all importance. A large number of the kitchens referred to by Mr. Gillott as working in 1918 were war establishments, and their use was discontinued when peace conditions returned. I cannot agree with Mr. Gillott that the number of British large-scale kitchens might exceed the American total.

I can assure Mr. McKenna that baking costs for bread and pastry are very reasonable and show considerable advantage to the baker if all the advantages of electric baking are taken into consideration. The maintenance of electric baking ovens varies considerably according

to the treatment they receive, but the replacement of elements in a well-known type of baking oven is practically nil, and other replacements are very few and then not of an expensive nature. It is difficult to see how detailed information about running cost can be given. Figures can only be given when they become available, and it is a very difficult matter either to persuade users of electric kitchens to keep proper records or, if they keep them, to disclose them. All that a manufacturer can say about maintenance cost is what spares he has to supply to each particular customer. The cost of spares plus the cost of necessary labour to carry out repairs constitute the cost of maintenance, and the percentages given in the paper are based on records of this kind. To give the loading of fish fryers per cubic inch has been considered the most satisfactory way.

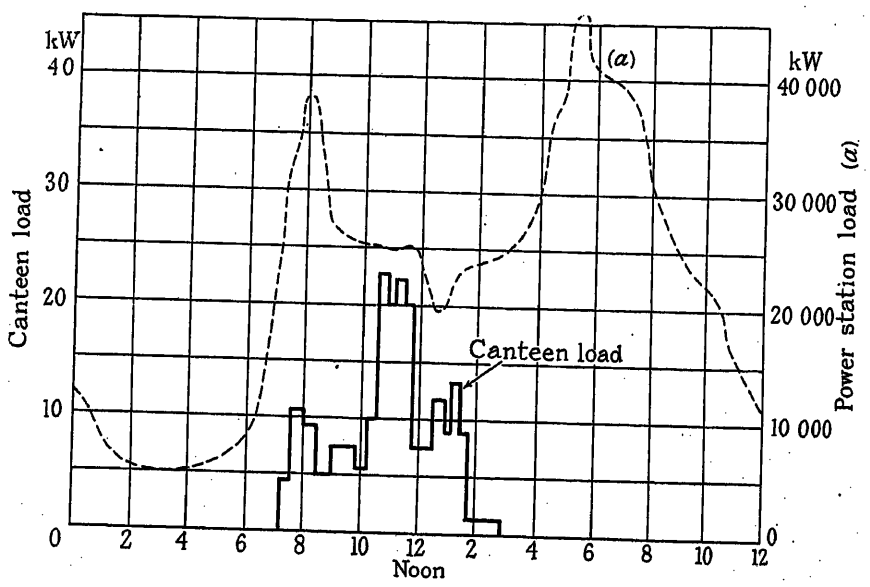


FIG. A.

A loading of 22 to 25 watts per square inch is considered satisfactory.

Whilst I agree with Mr. Benham that there is a good deal more heavy-duty electric cooking apparatus in use in London than in New York, I cannot accept his general statement that a very small amount of electric cooking is used in the United States. Both in New York and Chicago the electric supply is controlled by the gas interests. In Chicago, however, some of the very largest electric cooking installations in existence can be found. Where the gas interests are entirely separate, electric cooking has made great headway, and very important complete or partial electric equipments are continually being laid down in all parts of the United States. I am afraid I cannot consider Mr. Benham as an unbiased judge with regard to the merits of electric cooking. He is a manufacturer of cooking equipment of all types, and I am not surprised that he prefers other types of cooking equipment. This is one of the difficulties that the electrical industry has to deal with; it is responsible to a large extent for the general impression that electric cooking equipment is merely electrified fuel-fired equipment. The suggestion that gas at 8d. per therm is equivalent to electricity at $\frac{1}{2}$d. per unit is quite incorrect. I cannot do better than quote the figures obtained from an actual installation. In an important installation in the Midlands which was run entirely on gas, some time ago part of the gas equipment was replaced by electrical equipment. All roasting, grilling, and fish frying are now done electrically, whilst for all boiling, steaming, etc., gas is still being used. For six months weekly records were taken. The number of people supplied and the type of meals were practically identical. The total consumption of electricity for the purposes mentioned above for six months was 13 129 units. In the corresponding period of the previous year when gas was exclusively used, the total consumption was 452 300 cub. ft. The consumption of gas for boiling, etc., during the recent period was 99 300 cub. ft., so that 353 000 cubic feet of gas had been replaced by 13 129 units. At 1d. per unit the cost of electricity amounted to approximately £54. At 3s. 6d. per 1 000 cub. ft., or approximately 8d. per therm, the cost of gas was £62. These figures prove that the usual comparison between 1d. per unit for electricity and 8d. per therm for gas is a correct basis. There is no doubt that even if boiling also were done electrically the basis of comparison would not have to be altered. At $\frac{3}{4}$d. per unit, of course, the saving due to the introduction of electricity would be beyond any question. The figures published by Sir Dugald Clerk some years ago, which are based on a very doubtful calculation, give a comparison between efficiencies of gas and electricity as 42 per cent for gas and 59 per cent for electricity. These figures were very severely criticized by Mr. Highfield at a joint meeting of the Institution of Gas Engineers and the Institution of Electrical Engineers in 1920, and it will be admitted to-day, I believe, that these figures are not correct. I would put the efficiency of an average commercial gas equipment at about

40 per cent, whilst the average efficiency of electric apparatus could be taken as 80 per cent. These figures vary, of course, with the nature and type of apparatus. It is a very widespread practice of the gas interests to make the basis of comparison between gas and electricity the cost of coal at the gas works and at the generating station. We are only concerned with the efficiencies of gas and electricity as delivered to the consumer.

In reply to Mr. Fiander, I do not think that the figure of 58·4 per cent efficiency for gas apparatus is even claimed by gas authorities in this country. As far as charges for current are concerned, Mr. Fiander's statement is not borne out by the prices for current freely offered by supply authorities. A number are offering ½d. per unit and many ¾d. per unit. Unfortunately, there are no particulars available in this country as to the relation of a canteen load to the central station load, but I have been able to find a reference to this in *Elektrizitätswirtschaft Mitteilungen der V.D.E.W.*, No. 499, and Fig. A shows that the peak of the canteen load comes well within the valley of the central station load. Of course, this refers to a small installation catering for about 300 people.

In reply to Mr. Rawll, I do not infer that electrical equipment is ready for working directly it is switched on, but as far as boiling-plates are concerned, to which Mr. Rawll specially refers, they are ready much more quickly for boiling than an oven is ready for roasting. The reason for the lower loading for hot-plates customary in the United States is evidently that people there are less impatient with regard to boiling time than in this country. An induction type of cooker has not been referred to, because at the present time it cannot be considered either a sound technical or commercial proposition.

In reply to Dr. Sturley, apparatus for cooking on trains is usually designed to operate on any voltage between 180 and 220 volts. This wide range is necessary on account of supply being taken when the train is at a standstill, either from supply mains at the station or from the battery. Thermal-storage cookers are beginning to make headway for domestic purposes, but for industrial purposes they cannot be considered either a technical or commercial proposition. With the exception of baking ovens, which are of course an entirely different class of apparatus, I am not aware of any thermal-storage cooking on the Continent.

I think that Mr. Pittaway, who refers to a roasting oven fitted with a boiling plate or plates on the top, must have obtained a wrong impression of the slide shown. The slide in question referred to a method of removing the hot-plate for the purpose of cleaning or exchanging, but the hot-plate certainly did not form part of the oven top. The use of immersion heaters in fish fryers would not prove satisfactory; in fact there would be danger of the fat burning due to direct contact with the heaters. Immersion heaters would also take up valuable space in the frying pan.

Mr. Seddon must, I think, have misunderstood me when he refers to my introduction of a special type of oven ventilator. Opinions differ as to the necessity of eliminating steam in roasting ovens. Quite a considerable body of opinion attributes the better results of electric cooking to the presence of steam. I have not yet come across an industrial type of gas cooker which is heated externally.

I fully agree with Mr. Mears's remarks with regard to the efficiency and adaptability of the electric hot-plate as compared with gas rings. I agree that perfect contact between the surface of the hot-plate and the bottom surface of the cooking utensil is essential.

I can assure Mr. Gunn that electrode boilers of the type in which the electrode can be raised out of and lowered into the water would not be satisfactory in practice, and the use of high frequency for boiling purposes has so far only been dealt with experimentally.

Mr. Eccles's suggestion that boiling appliances on a.c. supply might be regulated by means of auto-transformers with a series of tappings is worth consideration, and experiments carried out in this direction may bring useful results.

DISCUSSION ON

"THE ELECTRICAL HEATING OF BUILDINGS."

North-Eastern Centre, at Newcastle, 9th November, 1931.

Mr. S. S. Jewsbury: Has the author found that a thermostat gives satisfaction in controlling the temperature of a room heated by means of a radiant panel? I suggest that an ordinary thermostat, which is operated by the air temperature, should not be used in rooms heated entirely by radiant panels, since it is admitted that the air temperature in such rooms is not a correct criterion of conditions of comfort. I also question the figures for the hot-water panel system given in Appendix X, page 1089 (vol. 69). The capital cost of both the plant and the structural work appears to me to be too high; also the depreciation cost has been based on the structural work in addition to the plant. I suggest that the annual cost of maintenance, etc., given as £200, should be reduced to £50. Even this is a higher figure than has been found necessary in connection with a much larger apparatus at Carliol House.

Mr. H. W. Clothier: A matter of vital interest to the whole electrical industry is the demand for storage load to keep generating plant working during off-peak periods. Apparently the average load factor at present is about 30 per cent, in which case an off-peak load of, say, 2 000 000 kW would be of immense service in flattening the load curve on the "grid" system. As an example of the extent of the water-heating load obtained for this purpose elsewhere, it is interesting to note that in Canada one maker alone has made 83 electric steam-generators with a total capacity of 850 000 kW. This great demand is due to the necessity of utilizing surplus power from hydro-electric stations where fuel costs do not enter into consideration; but assuming that our average fuel costs are of the order of one-quarter to one-third of our total works costs, the off-peak load becomes with us also an essential for maximum economy in the production and transmission of electrical power. It seems to me that the total average works cost of units generated could be nearly halved if a level load curve were possible. The late Dr. Ferranti told us in Newcastle a few years ago that water heating was the key to the problem of energy storage. The last time he spoke in London he said: "If I talked for the rest of my life I should feel I had not talked enough to emphasize the importance to the electrical industry of this question of storing the electricity produced." Having a strong faith in his prophecies, I think it behoves us to make a combined effort in all sections of the electrical industry to bring about this general economy. At present the heating of buildings and the demand for domestic hot water afford the main openings. The author's Appendices V and VI, valuable as they are in their present form as a statement of actual experience, would be improved if he brought them to a common basic denominator. In the discussion† before the Institution on the paper by Messrs. Monkhouse and Grant, it was suggested that a basis was necessary on which comparative calculations for different buildings and different purposes could be made. Could this not be called the "average heating factor," and signify the average watt-hours per hour required, over a day of 24 hours, per cubic foot of building capacity per deg. F. temperature-rise? As examples from published figures, this works out to 0·162 Wh in the case of Carliol House, which is an office building of 1 800 000 cub. ft. capacity, and at 0·38 Wh for a private house of 56 200 cub. ft. If the experience of several classes of buildings and methods of construction could be expressed in some such standard, it would be easier than it is at present to make a comparison with a table such as Appendix VI, where the number of days, hours per day, and average temperature-rise are left to the imagination. Further, if this standard were adopted such widely different figures as 0·060 and 1·23 kWh per cub. ft. per annum would be avoided. The attractiveness to the average user of the author's system of panel heating will depend upon its value as a storage system, and upon whether it will be accepted as such by the supply undertakings in determining the rates to be charged for the power used during off-peak periods. The author states that the Electricity Commissioners' Regulations for the Safety of the Public are contravened when electrode boilers are installed with the neutral point earthed through the resistance of the water. This type of boiler has been fitted in London, Glasgow, Manchester, and Newcastle, with the approval of the supply authorities, and the following remarks may help to clear away any formal difficulties in the path of electrode-boiler progress. The regulations applicable are: (*a*) Electricity Commissioners' Regulations El. C. 12a, Clause 3 (Insulation Test). This regulation says that the insulation of every circuit shall be so maintained that the leakage current shall not exceed one-thousandth part of the maximum current. (*b*) Regulation El. C. 12a, Clause 44 [Connection of Circuits with Earth (a.c. circuits)]. This regulation says that if an a.c. circuit is connected to earth, connection shall only be made at the place where energy is delivered to the circuit, and that this connection shall be made at the neutral point on the star winding. It also contains similar provisions to that set out in (*a*) above. A high-voltage electrode water-heater or steam-raiser is usually star-connected, and the whole of the water and metal work outside the controlling tubes is at the potential of the star point, which is definitely connected to earth through the shell (or through the neutral electrode, if one is fitted). This arrangement is shown diagrammatically in Fig. D.

* Paper by Mr. R. Grierson (see vol. 69, p. 1045).

† *Journal I.E.E.*, 1930, vol. 68, p. 676.

In another type of electrode water-heater or steam-raiser, the arrangement of electrodes is such that the load is delta-star, the star point being the neutral electrode. The shell is earthed, and the star point is connected to earth through the resistance of the belt of water between the neutral electrode and the shell. This is shown diagrammatically in Fig. E. Both these types of apparatus, whether for high voltage or for low voltage, contravene the existing British regulations for earthing. Moreover when earthing at more than one point is permitted, it may still be difficult to keep the out-of-balance current strictly within the limits required to conform with the specified permissible leakage current. The possible introduction of resonance due to multiple earthing must also be taken into account. But earthing the neutral at additional points through the resistance of the water should not disturb the operation of suitable protective systems. Leakage protection is unsuitable for parallel feeders and ring mains because the out-of-balance current due to an earth fault on one feeder would tend to trip out others on the same system.

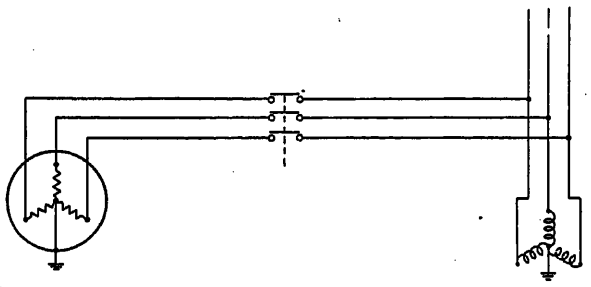


FIG. D.

This would occur with either single or multiple earthing of the system. The degree of trouble may be more severe when multiple earths are scattered over the system, but the inadvertent tripping is then attributable to the protective system, and not to multiple earthing. Leakage protection is intended for normal "tail-end" feeders, and is applicable, therefore, to electrode heating circuits earthed at the neutral; but it must be set heavily enough to prevent inadvertent operation due to the current through its earth path occasioned momentarily by an earth fault occurring on a feeder in the same vicinity. The minimum value of this setting would be $\sqrt{3}$ times the maximum load current. With the development of electrode water-heating on a large scale, it seems to me that we may require a revision of the practice of earthing, and that it may be helpful to earth the neutral at consumers' premises instead of at the source of supply. Given the necessary attention to this question of the earthing of the neutral, the electrode method possesses many advantages.

Mr. T. H. Carr: There is no question but that electricity is seriously handicapped, bearing in mind that the most efficient steam-driven turbo-alternator power station in this country at the present time has an overall thermal efficiency of not more than 24·5 per cent. It must be remembered that the commercial success of any power supply undertaking is absolutely dependent upon the cheapness and reliability of supply. Reliability must, however, take precedence over everything else, even over economy of production. With the introduction of the grid system interconnection will tend to promote security of supply and at the same time reduce the cost of reliability, but whether the cost of electricity to the consumer will be reduced to any great extent (as imagined by many) remains to be seen. On the other hand, the advantages of electrical heating are many, and its final cost to the consumer may in some cases be much smaller than that of other forms of heating. On pages 1058 and 1059 the author gives particulars of rooms, offices, etc., with normal window area. I should like to know what in his opinion is the normal window area of a control room for a power station. From information relating to the control rooms of 12 of the principal power stations in this country I find that the ratio of glass area to floor area varies from 15 to 100 per cent. This ratio affects the size of heating apparatus to be installed. Some authorities

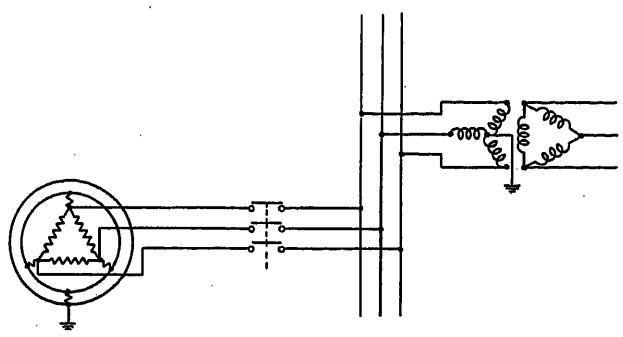


FIG. E.

state that this ratio should be not less than 20 per cent for workshops, etc., while others consider that the normal window area should be 20 sq. ft. per 1 000 cub. ft. of space in the room. Has the author had any experience of the application of thermostatically-controlled electrical heating apparatus to switch-houses and similar buildings, and, if so, could he give any reliable figures regarding the necessary number of air changes per hour and the allowable temperature-rise? I give below five methods of determining the size of thermostatically-controlled heating apparatus for a certain building, and I should be glad of the author's comments on them. Approximate capacity = 98 000 cub. ft.; area of glass = 4 300 sq. ft.; area of exposed wall = 1 000 sq. ft.; area of interior wall = 2 000 sq. ft.; area of floor = 2 800 sq. ft.; area of ceiling = 2 800 sq. ft. One complete change of air per hour. Temperature-rise = 23 deg. F. Sheltered on the north side, otherwise exposed.

Method (1).

No. of B.Th.U. per min. $= w\theta k_p$

where w = weight of air per min. $= \dfrac{98\,000 \times 1}{60 \times 12{\cdot}4}$ lb.

θ = temperature-rise = 23 deg. F.

$k_p = 0{\cdot}24$

Therefore

$$\text{No. of B.Th.U. per min.} = \frac{98\,000 \times 1}{60 \times 12{\cdot}4} \times 23 \times 0{\cdot}24$$
$$= 730 \text{ (approx.)}$$

Now

$$\frac{\text{kW} \times 1\,000 \times 33\,000}{746 \times 778} = \text{No. of B.Th.U. per min.}$$

Therefore

$$\text{kW} = \frac{730 \times 746 \times 778}{1\,000 \times 33\,000}$$
$$= 13 \text{ (approx.)}$$

B.Th.U. per deg. F. temperature-rise of glass, walls, etc., to allow for radiation losses (only approx.) $\frac{1{\cdot}0}{0{\cdot}3} = 3{\cdot}5$ approx.

Approx. kW capacity of heating apparatus

$$= 13 \times 3{\cdot}5$$
$$= 45 \text{ kW}$$

Method (2). *Wilmshurst's Formula.*

$$\text{kW capacity} = \frac{20{\cdot}4(30a + 8b + nc)\theta}{36 \times 10^5}$$

where

a = area (in sq. ft.) of window surface = 4 300
b = area (in sq. ft.) of wall, floor, and ceiling = 6 600
c = volume (in cub. ft.) of air in room = 98 000
n = number of complete air-changes per hour = 1
θ = temperature-rise of air (in deg. F.) = 23.

Therefore

$$\text{kW} = \frac{(30 \times 4\,300 + 8 \times 6\,600 + 1 \times 98\,000) \times 20{\cdot}4 \times 23}{36 \times 10^5}$$
$$= 37 \text{ (approx.)}$$

Method (3). *Young, Osmond, and Young's Formula.*

$$\text{kW} = \frac{AU\theta}{1\,000}$$

where

A = floor area (sq. ft.) = 2 800
U = 595 (for 36-ft. high room)
θ = temp. difference = 23 deg. F.

Therefore

$$\text{Capacity of heating plant} = \frac{2\,800 \times 595 \times 23}{1\,000}$$
$$= 38 \text{ kW}$$

If this formula is applied the normal glass area should not exceed 20 sq. ft. of glass per 1 000 cub. ft. of space. The formula therefore does not strictly apply in this case.

Method (4). *Grierson's Method.*

Section	Area	B.Th.U. per deg. rise*	Heat loss per degree	Temperature difference	Total B.Th.U.	Equivalent watts
	sq. ft.			deg. F.		
Glass	4 300	1·1	4 300	23	98 900	28 800
Exposed wall	1 000	0·3	300	23	6 900	2 000
Interior wall	2 000	0·3	—	—	—	—
Floor	2 800	0·4	1 120	23	25 800	7 500
Ceiling	2 800	0·4	1 120	23	25 800	7 500
Air (cubic feet) ..	98 000	0·02	1 960	23	45 000	13 000
Totals					202 400	58 800

* Taken from the author's table (see vol. 69, p. 1088).

Approx. capacity of heating plant = 60 kW

Method (5).

A figure of 0·8 to 1 watt per cub. ft. of building is sometimes used by architects.

Adopting the lower figure of 0·8,

$$\text{kW capacity of heating plant} = \frac{98\,000 \times 1 \times 0{\cdot}8}{1\,000}$$
$$= 78$$

Mr. W. Richardson: While I agree that the author's new system approaches the ideal form of heating, I think we have to admit that it cannot compete with other forms of heating on a purely commercial basis, when energy is charged at a rate which is profitable to the supply undertaking. There will, however, be a large field for this type of heating in small buildings and suites of offices where it is desired to avoid the complication of a central-heating plant and where satisfactory heating is important. So far as larger buildings are concerned, the author's system will be in competition with central-heating installations; throughout the paper he avoids any detailed comparisons between the two, confining his remarks to a general statement of overall efficiency. Table 16 shows the various losses which may occur on fuel-fired installations, and the author finally arrives at a figure of 15 per

cent for the overall efficiency of such systems. This value appears to me to be too low. Some inquiries which I have made regarding various local buildings show that the figure should be at least 30 per cent, assuming that 0·72 kWh per cub. ft. is the minimum amount of energy required during the heating season. The paper is unfair to thermal-storage equipments, which are stated on page 1080 to have a working efficiency of only 30 per cent. From this statement the author proceeds to make out his case for low-temperature panel heating, instead of thermal-storage heating. He gives a figure of 0·72 kWh per cub. ft. per annum for the consumption of the low-temperature panel system; a similar figure has been obtained with thermal-storage heating for large office-block buildings, and for a medium-size block of office buildings situated in an exposed position the figure during the second heating season was 1 kWh per cub. ft. Apparently there is not a great difference between the consumptions of direct and thermal-storage heating systems, but as a much lower rate for energy can be obtained for thermal-storage heating it naturally follows that the running costs of the latter are the lower. In Appendix X the author gives the energy consumptions for thermal-storage and direct heating as 562 000 and 441 000 units per annum respectively, which is contrary to the statement he makes earlier in the paper. The capital cost of the thermal-storage system is given as £10 300 for an installation of 368 kW, or approximately £28 per kW. An installation carried out in this city was completed for slightly over £9 per kW, and although this does not include thermostats and solenoid valves in each room, this omission would not account for the whole of the difference. If the capital cost of the installation were corrected, and a more reasonable figure given for attendance and maintenance, there would be an ample credit on the side of thermal storage. If electric heating is to be satisfactory, it is essential that installations should as far as possible be under automatic control. Whilst this is an essential feature of the low-temperature panel system, it can also be incorporated in thermal-storage heating. In the second case to which I have referred a thermostat situated in a central room is arranged to control the heating of the whole building. A time clock is also provided, so that heating can be started in the early hours of the morning to ensure that the offices are at the required temperature by 9 o'clock.

Mr. T. Carter: The Satchwell thermostat is an interesting device. It seems to depend for its much more successful working with alternating than with direct current on the fact that a short, not necessarily quick, break is perfectly satisfactory for the interruption of an alternating current, but not so for a direct current. Tests with much cruder apparatus, namely ordinary British Standard protected-type plugs and sockets (B.S.S. No. 196), have shown that, however slowly the plug is pulled out of the socket, a very small gap between the brass pins and brass contact-tubes is sufficient to open an a.c. circuit; and a series of tests at the National Physical Laboratory a few years ago proved the excellence of the operation of such plugs and sockets in a.c. circuits, even under abnormally severe conditions. Perhaps the metal of the contacts has to be carefully selected in an accurate controlling device like the Satchwell thermostat; but for mere circuit-breaking purposes the ordinary material of plugs and sockets is amply good. The point of importance is that the principle of circuit-breaking embodied in a refined way in the Satchwell thermostat can be applied widely in a.c. circuits generally, and its fullest use in suitably-designed apparatus would lead to much simpler switching than is usual to-day for alternating currents up to, say, 15 amperes at 250 volts. Incidentally, the word "freeze" is used in what seems to me a rather unusual sense in the tenth line from the foot of the left-hand column of page 1067. It is more commonly applied, I think, to the welding-together of contacts in a circuit breaker than to the mere solidifying of molten metal, strictly accurate as the latter meaning is.

[The author's reply to this discussion will be found on page 211.]

North Midland Centre, at Leeds, 10th November, 1931.

Mr. W. R. T. Skinner: The author is to be congratulated on co-ordinating in one paper so much scattered information and so many individual opinions on all aspects of this problem. I gather that he is in favour of low-temperature panel heating in preference to the many other possible systems, although he mentions (page 1055) that in his dining-room he has found a temperature of 55° F. with a 2-kW radiator to be "very comfortable indeed." On the ground of comfort I prefer the last-mentioned arrangement to the low-temperature panel system which aims at maintaining the relatively high and uniform air temperatures set out in Table 5. If we put aside for the moment all questions of artificial heating and consider what are the ideal natural circumstances of comfortable warmth, I think that most normally active individuals would agree that the best and most invigorating conditions obtain on those bright days in spring when the air temperature is comparatively low and the sun sufficiently high to be perceptibly hot. I suggest that the conditions most conducive to activity and work are a comparatively low ambient temperature with some form of high-temperature radiation, rather than uniformity of temperature of air and surroundings. Table 5 is in my opinion calculated to give rise to a large number of common colds. Living for a number of hours a day in uniformly warm surroundings seems to me to lower one's vitality and one's resistance to cold and colds. I would much prefer an ambient temperature of 50 to 55° F. supplemented by a high-temperature radiator rather than do without the radiator and have a uniform temperature of 65° F. A close approximation to what I suggest are the ideal outdoor conditions, demands the use of high-temperature rather than low-temperature radiators with possibly (at some future date) the addition of a small amount of ultra-violet radiation. I think that the radiators should be fixed to the ceiling or high up on the walls where they would be out of the way

and, beyond question, safe. For this purpose the bowl fire is eminently suitable as regards design, although it is not always large enough for heating large rooms. It is, however, well adapted to the heating of small rooms, especially the heating of bathrooms where the fact of the radiator being out of reach is of paramount importance. For the past 3 years I have heated a bathroom and a small bedroom in this way, the bowl fire in each case being fixed to the wall just below the ceiling. The author mentions consumptions per head for domestic use of 30 units per annum, with a possibility of 300 in the future. As the result of running a practically all-electric house for 5 years I find that the consumption per head has never fallen below 2 000 units per annum, of which rather over 40 per cent are absorbed by appliances for heating the house. In addition, two coal fires are in use during the winter. Only high-temperature radiators are used, the installed capacity being as follows:—

	Maximum loading of radiators	Net cubic content of room	Watts per cub. ft.
	kW	cub. ft.	
Dining-room ..	2·25	1 050	2·14
Sitting-room ..	3·2	1 460	2·19
Small bedroom ..	0·6	640	0·94
Nursery	1·0	1 040	0·96
Bathroom	0·6	400	1·5

A coal fire is used in the nursery in cold weather, the radiator capacity of 0·96 watt per cub. ft. being insufficient to deal with low-temperature conditions. I should say, however, that a radiator capacity of 2 watts per cub. ft. is sufficient to produce comfortable conditions within 10 minutes of switching on. As regards casual heat due to lighting, I find that the loading in the sitting-room amounts to 370 watts, or 2·4 watts per sq. ft. of floor area, this figure being equivalent to 11·5 per cent of the capacity of the radiator. I should like to know whether the author's figures in Appendices V and VI are based on the gross cubic capacity of the buildings or merely on the net cubic capacity of rooms, etc., heated. My own figures for 52 weeks ending 25th October, 1931, amount to 5 273 units used principally for heating (a small part of this consumption is due to kettles, an iron, and a vacuum cleaner, which are not separately metered), equivalent to 0·421 kWh per annum per cub. ft. based on the gross cubic capacity of the house and 1·148 based on the net cubic capacity of rooms heated wholly or in part by electricity. I estimate that the annual load factor is approximately 12 per cent. In Appendices V and VI the author distinguishes between the annual consumption of various thermal-storage and direct heating installations respectively. I have averaged those figures which are complete and find 1·69 kWh per cub. ft. per annum for thermal-storage systems as against an average of 0·517 for direct heating. If these are representative averages, the thermal-storage system uses something like 3¼ times as much energy as the direct system. Or, put another way, if one can afford to run thermal-storage systems at 0·25d. per kWh, one can afford to pay something like 0·8d. per kWh for direct heating. It is stated that low-temperature embedded panels produce no pattern staining on walls or ceilings due to deposition of dust. For what periods have these panels been in use without causing selective discoloration of the plaster or its decoration? The Department of Scientific and Industrial Research have recently investigated this state of affairs, and they attribute selective deposition of dust to the slight variation of temperature of the plaster surface resulting from the different thermal conductivities of lath and plaster. Variation of surface temperature must be much more marked where heating panels are embedded in the plaster, and it seems to me that pattern staining would be correspondingly accentuated.

Mr. G. Wilkinson: With reference to the low-temperature panel system, I installed one of the earliest water-heated panels (8 ft. long by 2 ft. 6 in. wide) opposite an alcove in my house some years ago, and in order to give a cheerful effect a rectangular recess was formed in the panel and fitted with a polished copper reflector and a lamp-holder, into which a 250-watt radiator lamp was inserted. As an illustration of the comfort and economy of radiant heat, I would state that whereas a temperature of 60 to 62° F. is required for comfort in a sitting-room heated in the ordinary manner, the alcove is quite comfortable with the thermometer reading 3 or 4 deg. F. lower. Table 1 mentions iron, oil, and water as three practicable heat-storage media. Three or four years ago in visiting a church heated electrically by the well-known tubular system, I found that the alarmingly high maximum load of 230 kW was taken by the installation. This figure indicates at once that success from the economic standpoint for electric heating does not lie in the direction of hand-to-mouth methods of that type, but that some kind of thermal-storage system must be adopted. The author deals in detail with hot-water storage and non-storage methods of electric space heating only: I wish to speak of the use of cast iron, as I have recently had some surprising experience of its heat-storage properties. Although Table 1 gives the maximum working temperature of iron as 700° F., it is futile to expect iron to emit much heat at so low a maximum temperature. By way of illustration of this point, if a poker is put into the fire and withdrawn when it is red hot, say at 1 200 to 1 500° F., it will lose its glow very quickly, i.e. the emission of heat to the atmosphere will be rapid, but after it has cooled to a black heat the emission becomes less and it is a long time before it becomes cold enough to be handled at the heated end. Again, castings and steel ingots soon lose their glow on emerging into the open, but as they cool the heat emission becomes slower and is extremely sluggish at the lower temperatures. I have in my house a space heater in which cast iron is the heat-storage medium, the temperature of which rises to about 1 400° F.—a dull cherry red. The heat emitted from this glowing mass is transferred to a low-temperature surface, the working temperature of which is taken care of by a room thermostat operating upon a heat-emission valve placed between the heated mass of iron and the outer casing. In this manner the heat emission to the

apartment is automatically regulated independently of the temperature of the heated mass of iron, the maximum temperature of which is also controlled automatically by a simple device. Table 1 gives the minimum working temperature of iron as 200° F.; this again is a practically useless figure, as one cannot profitably employ cast iron at temperatures lower than 300 to 350° F. Below this figure the rate of heat emission is too slow for most practical purposes. If good results are to be obtained, the working range should not be less than 1 500–350° F. This gives the high heat-storage figure of 150 B.Th.U. per lb. of iron and changes the whole aspect of the problem of successful thermal-storage heating. Instead of storing 29 800 B.Th.U. in a cubic foot of iron—at a capital cost of 18s. 8d., as set out in Table 1 (some of this being practically useless, due to its low temperature)—we get 67 500 B.Th.U. per cub. ft. at a capital cost of something like 6s. only per 10 000 useful B.Th.U. stored. If the heat-insulation sleeve and valve be lifted off the glowing mass of iron the room temperature goes up quickly to a point which is distinctly uncomfortable; this, however, is a valuable characteristic, showing as it does the extreme flexibility of heat storage at high temperatures in cast iron. It also has a high economic value, as a heater of given rating can be called upon to perform the double duty of continuous heating and the quick heating of a cold apartment, the maximum demand for a given building being halved thereby. This should have the good effect of enabling considerably lower tariffs to be offered for such supplies without in any way decreasing profits. Many designs embodying the distinctive features of this type of heater may be made. The non-storage heating panel mentioned at the outset is built of 30-in. by 16-in. sections each of which weighs 35 lb. and emits 2 760 B.Th.U. per hour. In its simplest form the heat-storage apparatus consists of an outer vertical cylinder of planished sheet steel with a centre core of cast iron in the form of a column of square section. This is surrounded by a sleeve of sheet metal sliding over the column and furnished with insulating flanges at each end, the upper flange carrying a valve which controls the heat emission to the outer casing which may in turn be controlled by a room thermostat, as already described. The casing between its upper and lower flanges is wound with thin crinkled aluminium foil in 4 to 6 layers, which constitutes a surprisingly good heat insulation, the whole being covered on the outside by an enveloping cylinder of sheet tin. This concentric casing can readily be lifted in and out of the heater; it is arranged with a clearance below so that air from the outer casing can circulate between the heated iron and the outer heat-emission cylinder. The necessary ducts in the hot chamber are provided by the passages on the four sides of the heat block formed by its flat sides and the curved surface of the enveloping sleeve of sheet metal. Referring to Appendix X, the estimated capital costs given are £10 300 for the hot-water storage system and £5 300 for the panel system. With cast-iron heaters of the type already described one can get the same number of heat units and an equivalent distribution of heat for a capital outlay estimated at £2 500 to £3 000. The annual costs are given as £1 974 and £1 630 respectively. With cast-iron storage each heater is self-contained and there are therefore no heat losses due to radiation from pipes or tanks, and there are no circulating pumps to run; therefore the 25 per cent extra kWh allowed in the hot-water system to meet these losses must be deducted, and the annual energy consumption becomes the same as for panel heating, viz. 441 000 kWh per annum. The iron storage-heaters take their current during off-peak hours and the units consumed are therefore chargeable at the storage rate of 0·3d. per unit quoted by the author, instead of the 0·594d. per unit for the non-storage panel system. Allowing the same percentage for interest and depreciation as is set down for the panel system, and adding the £10 per annum for attendance, the annual cost comes out at only £761, or over 100 per cent less than for the non-storage panel system. In this figure no allowance is made in respect of the substantially-decreased maximum demand required due to the extreme flexibility in the output of this class of heater.

Mr. H. G. Fraser: I think that we ought to be very cautious in preparing estimates for electric heating on a fairly big scale, otherwise we are likely to do the industry a great deal of harm at the outset. If, on the other hand, electric heating is carefully tackled, it will lead to opportunities of greatly helping the industry. I have a few figures for tubular heating that may prove interesting. They represent an elementary-school installation which has been in service for a little over two years, thermostatically-controlled tubular heaters being employed throughout. The total installed capacity is some 140 kW and the maximum demand rarely, if ever, exceeds 130 kW, this load invariably coming on between 8 and 10 a.m. Usually the full load is on at 8 a.m., and the load gradually decreases as the thermostats come into operation. Towards 10 a.m. the load is probably 100 kW. In the afternoon the load comes on again for a short time just after lunch when the school opens, but not to the same extent. It never exceeds 100 kW in the afternoon, and it gradually falls at about 3 p.m., when there is probably less than half load on, given a reasonably cold day. At 3.30 p.m. 20 or 30 kW are being taken, and the whole load is off at 4 p.m. Although it does not affect the power-station peak, the load is not a cheap one to supply. The flat rate at which we give this supply at present is 0·55d. per unit. The consumptions for the last two years have been 86 000 and 96 460 units respectively, which work out at roughly £196 and £216 per annum. If it is true that the installation enables the school authorities to dispense with the caretaker's labour, etc., the proposition is a good one from their point of view. If it is not true, however, the price will have to be reduced, assuming that no great value is set on the superior convenience and cleanliness of electric heating. I think that in an industrial district, certainly in the West Riding of Yorkshire, the convenience, etc., of the electrical installation is not assessed at so high a value as it is in other parts of the country. We have established that this type of load is a distinctly "off-peak" one so far as the power station is concerned, but it is only on for the winter months and is not used in June, July, August, and September, except occasionally. The supply always

has to be available, however, because with electric heating the necessity for shutting down the school heating system for a fixed period during the summer regardless of temperature, does not arise. The electric heating system is always available and is used accordingly.

Mr. E. A. Logan: I worked for a considerable period in a large building equipped with a thermal-storage heating system with embedded panels, and one of the features which impressed me most was the enormous effect of air humidity on the feeling of warmth experienced. I found that when working at a temperature of 63° F. on a dry day quite a number of people complained of being too hot, whilst on a foggy day they complained that they felt cold at the same room temperature. I think that not only will the embedded-panel system suffer from this variation of sensation with humidity, but so also will the thermostatically-controlled system. In time engineers will no doubt evolve a new thermostatic system which will take account of the humidity. I found that if a wet overcoat was hung up to dry in the building to which I have referred, it was just as wet a few hours later, because in the highly saturated atmosphere the moisture percolated through the coat without drying out. The garment thus became practically useless for the time being. In some of the first buildings to be heated electrically the ventilation problem was rather neglected. I think that the engineers responsible for the designs were rather concerned at the amount of heat they would lose if the ventilation were adequate. The problem has been dealt with better in later installations and in at least one case a rather elaborate air-conditioning plant, involving a certain amount of regeneration, has been installed. The author may be able to give us some details of this system. The paper reveals that new kinds of fixtures and a new electrical heating technique are being developed. Materials are being used which do not belong properly either to the electrical or to the building trade, but partly to both. I should like to know how the labour question is dealt with on these heating installations. In London, in particular, there are at present very great difficulties in this connection. For example, if an electrician requires a hole through a wall he has to have a bricklayer's labourer to make it. One great advantage inherent in an electrically-heated building with embedded heaters is worthy of comment. Sometimes in the spring there is a rapid rise of air temperature coupled with a high degree of humidity. Under this condition in a building with cold walls and floors, particularly with marble panels or painted surfaces, a distressing weeping effect is created by water running down the walls. This does not occur in an electrically-heated building, due to the walls being warmer than the surrounding air. I am interested in the easily-applied heating method which the author has evolved, but I should like to know whether the material used is non-inflammable. I have recently had an unfortunate experience with a low-temperature heater made of an inflammable material. The latter being in a dry state, when slight arcing occurred it began to smoulder. With regard to the question of high-temperature versus low-temperature ceiling radiators, can the author give any information as to the possible physiological effect of high temperatures overhead? I have heard it suggested that high-temperature heating placed overhead is liable to set up a condition closely approximating to sunstroke. Fig. 15 gives the results obtained with a thermostatically-controlled non-thermal-storage system, a system which the supply engineer is rather inclined to disparage from a load-factor point of view, fearing that the incidence of the heating load will add to his normal load peak. It will be seen that the curve is almost the obverse of a normal load curve, with the exception of a period about 9 a.m. I think Fig. 15 is worthy of study by the supply engineer from the point of view of levelling the load on his mains.

Mr. R. M. Longman: Mr. Wilkinson has, I think, gone a long way towards saving the situation for the supply undertakings, by a system of heating iron up to a temperature of about 1 700° F., which reduces the cost and completely alters the figures for Appendix X. His method is rather similar to that adopted in the thermal-storage systems used in Norway and Sweden with great effect and satisfaction. If we can develop on those lines, there is great hope for industrial electric heating. I should like to ask Mr. Wilkinson the weight of the heater which he has in use at his own house. Before coming to this meeting I felt that we ought to pay special attention to thermal-storage systems to assist in filling up the night valleys in the load curves. The ideal load would come on any time after 9 p.m. and go off at 9 a.m., with a refresher between 12 noon and 2 p.m., and partial load after 5 p.m. In a certain town they were recently considering heating the schools and public buildings electrically, and the engineer was very sceptical as to whether this would give such an increased demand in the morning that the peak would occur in the morning due to this industrial heating. I trust that he has carefully studied the paper and consequently feels reassured on this point. Domestic heating is quite a different proposition from industrial heating. As a substitute for a coal fire one must provide something that is pleasant, attractive, bright, and cheerful. My home installation, which heats an 8-room house occupied by 6 persons, has a consumption of 9 000 units per annum for all purposes, but coal fires are used in the kitchen and dining-room during the winter. All the cooking and about 75 per cent of the water heating is done electrically. What is wanted is an increase of the domestic load, which is always with us, both in good times and in bad.

Mr. W. Dundas: The supply engineer must spread the author's enthusiasm for electric heating if progress is to be made. The task is by no means easy, the load being entirely seasonal, thus adding to the demand on the station at times of heavy loads and thereby mitigating against the requirements of a low tariff, upon which the success of electric heating from the point of view of the supplier is primarily dependent. Winter-evening peak-load hours must be ruled out entirely, which indicates that electric heating will certainly have to rely on heat storage on the consumer's system. Again, the load curves shown in Fig. 15 indicate a decided peak at 9 a.m., and it is quite conceivable that that peak may rise considerably with the development

of the heating load unless some restriction be made to cover the period in question. From experience of steam heating, I am convinced that it will be necessary to get down to a low figure in the region of 0·2d. per unit to attract custom, but this figure is permissible only during off-peak hours. The more efficient application of electric heating compared with the other systems mentioned by the author, together with other advantages, will assist, no doubt, in obtaining a more economical overall price per kWh. The heating load is attractive inasmuch as it will help to fill the early-morning gap in the load curve, about which all supply undertakings are much concerned, and whether the advantage thus obtained will enable an attractive day-load tariff to be secured calls for careful investigation.

Mr. G. W. Jenkins: I should like to add a word to Mr. Logan's remarks about humidity in connection with electrical heating. I believe that a lot of the smell, or the "stuffy" feeling, that has been mentioned in the paper and by other speakers is due to the excess of humidity set up by fairly high-temperature heating. A radiant-heat system enables one to get a degree of comfort by maintaining a very much lower temperature of the room, and the thermometer is therefore not necessarily a guide to the state of comfort of the individual. I believe that a lower temperature gives rise to a lower degree of humidity and therefore tends to eliminate "stuffiness" and smells while still maintaining the state of comfort of the individual. Perhaps the author could enlarge upon this particular feature. Mr. Longman has mentioned that the conservative ideas of electrical heating held by some people in this country make them insist upon seeing the source of heat, i.e. some sort of glow. I think that this is a matter on which electrical supply engineers should educate the public. In travelling America from one end to another one never comes across an open fire. Evidently the Americans have been educated up to the degree where they can feel comfortable and warm without seeing the source of heat, or any kind of glow.

Mr. C. F. Wells (*communicated*): Whilst I agree that thermostatic control is generally desirable, I think there may be a danger of the electric system losing some of its advantages if rooms in occasional use only, such as bathrooms, are continuously maintained at a temperature of, say, 60° F. In a 6-room all-electric house I carried out the whole of the heating with electric fires for a consumption of 6 800 units per annum, which worked out at 1·1 units per cub. ft. per annum. On the same basis I estimate that there is a potential market for 200 to 300 million units per annum for the heating of houses in the United Kingdom. One of the installations for which my company has been responsible is a Roman Catholic church where 40 kW of tubular heaters are installed. In this case the consumption is 9 800 units per annum, which works out at 0·1 unit per cub. ft. per annum.

[The author's reply to this discussion will be found on page 211.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH DECEMBER, 1931.

Mr. E. A. Reynolds: It is now recognized that electric heating has entered into competition with other methods of heating buildings and that as regards cleanliness, adaptability, ease of control, and variety of application, it has advantages over those. There are, however, two other considerations—comfort and economy—to be taken into account. The sense of comfort of the human body as far as warmth is concerned depends much more on the heat received by radiation than on that received by convection. A much greater sense of comfort is experienced in a room where the air is moderately cool and radiant heat is acting on the body, than in one where the air is heated to a higher temperature without any radiant heat. A low air-temperature is also an advantage from the point of view of health. Radiant heat makes it possible to have better ventilation and even open windows without feeling that heat units are being extravagantly wasted by driving the heated air out of the room. We have all experienced the feeling of healthy comfort given by bright sunshine in a still atmosphere that is well below freezing-point, and this is a good object lesson to guide us in our efforts to give comfortable and healthy heating of buildings, and more particularly of the living-rooms in our own houses. This end can be more satisfactorily attained by electric heating than by any of the other systems. Probably the most economical and healthy way to heat a living-room would be to install some form of low-temperature heating such as electric panels or tubes, so as to maintain a moderate temperature, and to augment this by an electric radiator of the reflecting type. This would provide a definite source of radiant heat which can be moved to any part of the room, and which in addition to its heating effect would introduce a centre of interest which is absent in uniformly heated rooms. The question of the general use of electricity for heating depends entirely on the relative cost of electrical and other systems, bearing in mind the advantages peculiar to electric heating. The fact that the unit of electrical energy represents 3 415 B.Th.U. has been extensively used as an argument against the use of electric heating, by comparing this quantity of heat with the very much larger amount of heat energy represented by the amount of coal necessary to produce that electricity. This is, however, quite beside the point, as the important question is the actual cost of obtaining heat at the particular position in the form required for comfort. This figure is best settled in actual practice, and it does not depend entirely on the fundamental facts of the theory of heat and calculations of heat losses in various forms. The essential factor in the general use of electric heating is, therefore:—What is the lowest price at which the supply authority can afford to distribute this energy, and at that price is it economical for the consumer to use that energy for electric heating? The author states that it is more economical to maintain the temperature of a building constant throughout the day and night, than to allow it to fall during the night and be raised again the next morning, and also that under many conditions the load is a minimum during the late after-

noon. If this is the case, such a heating load would be an ideal one from the point of view of the supply authority, and it should be charged for at the lowest possible rate. In some areas current for this purpose is now being sold at ½d. per unit, and in other areas this price is charged for domestic water heating and for heating loads in factories. Thus there is apparently no reason why the continuous heating load for private houses and public buildings should not be charged at the same rate. If supply authorities were to adopt this rate for such purposes, the probability is that they would soon have to increase the size of the distribution mains in the centres of large towns to deal with the increase of continuous output that would have to be met.

Mr. F. C. Platt: Although, as the author remarks in his Introduction, the seeds sown by the Electrical Development Association are bearing fruit, a good deal remains to be done in the way of education, and the amount of money spent on advertising in the lay Press should be tremendously increased. Regarding his statement that more attention is being given to electrical matters by the lay Press, I am of opinion that public services have no news value unless they go wrong; thus a tube failure at the rush hour, a black-out in the West End of London in the evening, the fume question, etc., all constitute news, whereas the application of electricity does not. The germ of the whole paper lies in the comment (on page 1080) regarding pollution of the atmosphere. The public does not realize the extent of the injury to health and fabric caused by smoke, and a determined effort to suppress this nuisance would direct the public mind towards the desirability of using electricity generated in power stations where fumes can be rendered innocuous before being discharged to the atmosphere. We are practically no further advanced than in mediæval times as far as domestic space heating is concerned, and in this connection I would deprecate excessive emphasis on the financial aspect. Surely the virtues of electrical space heating are worth the slight extra cost. At the risk of seeming inconsistent, I submit the following figures for comparison with those given in Appendix VIII.

Type of Building. Single-story mills; north-light roof.
Heating Season. 30 weeks.

Type of Heating.
Works A. Steam 185 lb. per sq. in., superheated 100 deg. F., reduced to 60/90 lb. per sq. in., and circulated through pipes suspended at 9 ft. above floor-level.
Works B. Steam generated at 40/60 lb. per sq. in., saturated, circulated through pipes as in "A."

Volume of Building.
Works A. $12{\cdot}1 \times 10^6$ cub. ft.
Works B. $1{\cdot}16 \times 10^6$ cub. ft.

Total Slack Burnt.
Works A. 2 422 tons.
Works B. 392 tons.

Total Steam Supplied.
Works A. $33{\cdot}67 \times 10^6$ lb.
Works B. Not recorded.

Slack per cub. ft.
Works A. 0·45 lb.
Works B. 0·756 lb.

Steam per cub. ft.
Works A. 2·78 lb.
Works B. Not recorded.

The whole of the figures are for 30 weeks.

Fuel Used. Slack, about 9 500 B.Th.U. per lb. as fired.

Mr. J. Anderson: It is a great pity that so much endeavour should have been expended in so poor a cause as the one championed by the author. He himself appreciates that it is a bad cause, for in the Introduction he states:—"Very many technically-trained men at present hold the opinion . . . that electricity is hopelessly handicapped." If he had substituted "all technically trained men know" he would have been nearer the truth, because to heat buildings economically by electricity is impossible. It is only when economy becomes less and less important, and convenience—whether of use or of installation—becomes more and more essential, that a case can be made for electrical heating. In the heating of a workshop the problem is presented in its simplest and crudest form, for there economy is imperative. I have worked out the following costs for two workshops. The first is a large workshop covering nearly 3 acres, with a total cubic content of approximately 1½ million cub. ft. The plenum system is used; low-pressure steam raised in a boiler passes through pipes to nests of tubes over which air is blown by electrically-driven fans into large ducts carried the length of the buildings. The condensed water is pumped back into the boiler, and only a very little make-up water is needed from time to time. The shops are usually very comfortable to work in, although on very cold mornings when the stoker has not kept the fires up the temperature has on some occasions been rather low for the first hour or two. The system was started 14 years ago, and was extended as the works grew. With coal at 20s. per ton, stoking at £4 14s. 6d. per week, and electricity at 0·96d. per unit, the cost works out at 0·000021d. per cub. ft. per hour over the whole 12 months, i.e. 8 700 hours. Assuming 14 000 B.Th.U. per lb. of coal, there are 1·48 B.Th.U. per cub. ft. of air space per hour at the coal heap. Taking October to April (5 100 hours), the corresponding figures are 0·0000345d. and 2·43 B.Th.U. Turning to the author's figures for a London office, although he buys electricity at 0·675d. per unit as against the 0·96d. which a large consumer has to pay in Birmingham, his cost is 0·000095d. per cub. ft. per hour over 5 100 hours, and there are only 0·485 B.Th.U. in the air. Assuming the efficiency of the steam plant to be only 50 per cent, the electrical cost at 0·675d. per unit would be 6·9 times the present cost, and at 0·96d. it would be 9·8 times. The second case is that of a small workshop 60 ft. × 20 ft., the volume being 11 700 cub. ft. It is partitioned into three parts, 40, 10, and 10 ft. long. The

40-ft. part is heated by a specially designed gas heater located towards the partitioned end; the flue is carried along the centre of the shop and passes out through the end gable. The temperature of the discharge gases is about 112° F. The other two parts are heated by eight resistances, two under each window, and they are run either at a dull red heat or just below it. A comparative test was made on a mild day with no sun, no fog, no rain, and very little wind, when the outside temperature was constant at 42° F. throughout the duration of the test. The temperature at 5 ft. from floor-level in the gas-heated part was 57° F. at the coldest spot and 63° F. at the bench nearest the stove. Similar figures for the electrically-heated part were 59° F. at the coldest and 61° at the warmest, so that the mean temperature was the same in both cases. The price of gas is 7·79d. less 5 per cent per therm (3s. 1d. per 1 000 cub. ft., less 5 per cent), and of electricity 1½d. per unit. The results were 0·000336d. per cub. ft. per hour for gas, and 0·0018d. per cub. ft. per hour for electricity, or electrical heating was 5·35 times as costly as heating by gas. The largest consumers in Birmingham buy gas and electricity at about 62 per cent of the price I pay, so that the ratio would remain unaltered in their case. Taking the efficiency of the electric heaters as 100 per cent, the B.Th.U. supplied to the air per cub. ft. per hour are 4·05, and taking the official figure of 475 B.Th.U. per therm for the calorific value of the gas the corresponding figure is 4·55 B.Th.U. per cub. ft. per hour. This makes the efficiency of the gas heater 89 per cent, which is quite a likely figure in the circumstances. That there is not much wrong with my figures for electricity is shown by the fact that if one reduces 0·0018 in the ratio of the price per unit and the B.Th.U. in the air, one gets 0·000097 as against the author's 0·000095. Coming higher up the scale to small houses of £50 to £80 rateable value, the position is a little more favourable. I have lived in and fitted out six houses in the past 25 years; the first two were completely gas-heated, except for the water heating, the next was equally completely electric, the next two were gas, and the last has a mixed system—coke, coal, gas, and electricity—which I am satisfied is the only one giving the maximum of comfort and convenience at a reasonable price. Continuous heating, advocated by the author, is not attempted and it would not be of much use since the whole house is thrown open to the four winds of heaven from 9 a.m. to 12 noon, and some of the windows are practically never closed. Only the fixed charge plus ¾d. per unit makes the limited use of electricity for heating at all possible; the overall charge works out at 0·985d. per unit for all purposes in my case.

Prof. W. Cramp: The author omits all reference to the physiological aspect of electric heating, although this appears to me to be the factor which, in the future, will control the type of radiator. The recent experiments of Prof. Leonard Hill lead one to believe that low-temperature radiation should not be encouraged, and my own experience is in exactly the same direction. Children are very good and unprejudiced judges of what is comfortable. I had a nursery and for some years it was heated by means of an anthracite stove, which maintained an even temperature of about 60 to 65° F., day and night in the room, yet the children constantly complained of feeling cold. I substituted a radiator of the lamp variety, which was switched on about half an hour before the room was used, but in a very short time after entering the room and remaining in the direct radiation the children asked that the radiator should be switched off, although the temperature was only 50° F. This occurred repeatedly, and an analysis seemed to show that the effect of the radiation was to stimulate the action of the skin, so that the natural circulation materially improved, and the effect of warmth was produced without that dryness of the air and excessive evaporation from the skin which accompany all systems that give a uniform air-temperature. I believe that direct high-temperature radiation is much more akin to the effect produced by summer sunlight than any kind of low-temperature radiation or convection heating, and in addition the cost of heating electrically by such means is very much lower. The transfer of heat also is quite different, when such radiation is employed. Dark objects, including practically all furniture, absorb the radiation and rise to a temperature higher than that of the surrounding air, which is in accordance with what takes place under pleasant conditions in nature. As a result, no feeling of cold is experienced in touching such objects, whereas if the heat be transferred to the air first and to the furniture through the air, the opposite effect is produced. It may be useful to add a comment upon the calculations which are usually made in connection with coke stoves. The conditions which obtain in practice are not at all the best for producing that high efficiency which is often quoted. In most offices and houses the coke stove runs for many hours with bright burning fuel at the bottom and cold coke at the top. In consequence, it acts as a producer, turning out large quantities of carbon monoxide, which pass away up the flue. When the bulk of the fuel becomes red hot, this gas can be seen burning with its characteristic blue flame in the upper portion of the stove, and only then is the stove efficient; for the quantity of heat given out by the change from coke to carbon monoxide is far smaller than in the change from the monoxide to the dioxide.

Dr. L. G. A. Sims: I should like to comment upon Section 11 (page 1050) of the paper, which is apparently based upon information given in the recent paper on "The Heating of Buildings Electrically by means of Thermal Storage"* and perpetuates what seemed to me a somewhat serious omission from that paper. I refer to the omission of information relating to the unit type of thermal-storage heater employing as the storage medium blocks of suitable stone or of iron, instead of water or oil. Circulatory liquid storage systems are not the only ones worthy of consideration by the heating engineer. In my opinion both the floor-heating system used abroad and the unit-type heater should have been mentioned by the author, particularly as he criticizes the hot-water system rather severely. Information relating to the floor-heating system of thermal storage will be found in the contribution which I made to the discussion† on the paper by Messrs. Monkhouse and

* S. E. Monkhouse and L. C. Grant: *Journal I.E.E.*, 1930, vol. 68, p. 657.
† *Ibid.*, vol. 68, p. 698.

Grant, and I propose on this occasion to confine my remarks entirely to the unit type of heater. This consists of an accumulation core of blocks of cast iron or suitable stone enclosed in a heat-insulated casing. While an iron core is very convenient for manufacturing reasons, its weight is a slight disadvantage. A stone core is very much lighter, but as it has rather less storage capacity per unit weight it must, in general, be run at a somewhat higher temperature than one of iron. Furthermore, many forms of stone are unsuitable on account of their poor thermal and mechanical properties. In a heater of the unit type developed at the University of Birmingham from a rather crude and inefficient model to an efficient and practical heating device, cast iron was used.* For a model rated at 2 kW (8-hour charging period), the overall dimensions are approximately 20 in. × 20 in. cross-section by 33 in. height. The heater, even in this small size, has an efficiency of approximately 90 per cent. With this form of heater storage takes place, in the room to be heated, so that no boiler room is necessary and therefore much of the

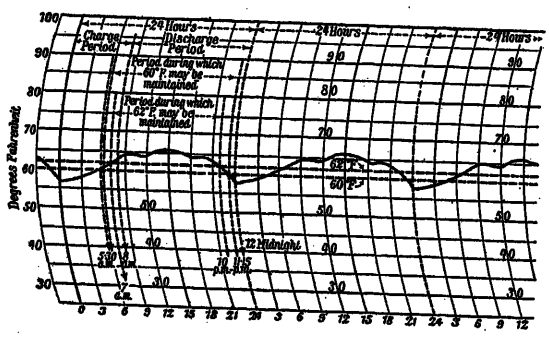


FIG. F.

author's criticism of the thermal-storage system using water does not apply to this system. There is even a case for claiming 100 per cent efficiency for it rather than the 90 per cent quoted above, as all the heat developed is liberated in the room. As the author points out, the room-temperature characteristic is an important matter with any form of heater, and the unit-type solid-core heater requires careful design in this respect. Though early models were not entirely satisfactory, the heater in its latest form meets all reasonable demands. A room temperature constant within less than 5 deg. F. during 15 hours may be obtained by means of it. Fig. F shows a thermogram taken with one of these heaters in a room with closed windows over a period of 3 days. It will be seen that during 11 hours of the working day the temperature was maintained at 65° F. constant to about 2 deg. F., and that over 15 hours the temperature did not fall below 62° F. or rise above 66° F. It has to be remembered that this performance was given by a heater which can be erected by any contractor in a few hours in an existing room, no alterations to the structure nor additions of any kind other than the usual wiring being necessary. Moreover, the heater is in circuit only during the night (in the case described above the charging period was 8 hours) and so qualifies for the maximum "off-peak" rebate. No difficulty is encountered in meeting the requirements of supply authorities for different "off-peak" periods. For example, a satisfactory design was recently evolved for a case in which the heater could be allowed to remain in circuit all day except between 10.45 a.m. and 12.45 p.m. and between 2.45 p.m. and 5 p.m.—a very long charging period. The heater is even more suitable if only a short charging period is available, provided that this occurs after midnight. I am very sanguine that unit-type thermal-storage heaters will meet a need in such service as, for example, office heating, where 20 to 30 kWh per day are sufficient, provided that a small amount of floor space can be spared. They ought to be better known, for I believe they will do the work required of them more economically than other methods.

Mr. H. Hooper: The subject of electrical heating opens up such a wide field that practical figures are of interest at this juncture. It is my opinion that future electrical development in this country will be along the lines of the paper, including further domestic electrification. The following are the details of an actual installation of tubular heating for a block of large offices consisting of 20 rooms and 4 garages. Connected load = 84 kW; number of units consumed in one year = 83 000; 1 201 ft. of tubing and 31 thermal switches were installed. The value of such a system in any area would depend entirely upon the price per unit obtained, but tubular heating is not in my opinion a practical proposition at a tariff exceeding ½d. per unit. I should like to refer to an attempt to put in a thermal-storage system in a building of 30 000 sq. ft. floor area; schemes were obtained for an 850-kW installation to give a temperature of 55° F. The capital cost was found to be from £4 000 to £5 000. For a temperature of 45° to 50° F. alternative schemes were put forward of approximately 450-kW loading, at a capital cost of £3 000. Even if this difficulty of high capital cost had been got over it would have been impossible to obtain a satisfactory price per unit, 1d. being the lowest figure available. In this case it was found that electricity could not be used, and an oil-fed steam system was put in at a cost of approximately £900. It is my opinion that for the heating of large works, warehouses, etc., by thermal-storage off-peak supply, the price per unit will have to be a small percentage on the supply station's coal costs.

Dr. R. D. Gifford: I was surprised to see amongst the illustrations a view of the office in which I work. I refer to the lower figure on Plate IV. This shows one floor of a 4-story block of offices heated on the tubular system, the total load being about 120 kW. It will be seen that the tubes are placed within 6 in. of the window-sill level, and not on the skirting board as depicted in Fig. 1. There are three reasons for this. First, to combat most effectively, by convection, the down-draughts from the windows; second, to increase the effective radiating arc, which becomes about 85°, as against the 60° mentioned by the author on page 1048; and third, because these tubes are not intended to be stood upon, and the easiest way of preventing this is to place them where it is not likely to be attempted. It

* L. G. A. SIMS and K. R. STURLEY: "Solid-Core Thermal-Storage Heating Units," *Engineering*, 1931, vol. 131, pp. 561, 664.

may be argued that in this position there is a likelihood of people getting burned, but in three years this has not happened. The heating is controlled thermostatically. When first installed, in 1928, there was only one thermostat per floor, but this was not a success, as the temperature at the thermostat did not necessarily represent that elsewhere, for example near a door or open window. These thermostats were therefore replaced by the type mentioned by the author, each controlling about 30 ft. of tube—some 2 kW. In Table 4 the author places this type of heating in class C owing to its effect on decorations. From my experience I should place it in class B. I do not find myself in agreement with the author when he advocates continuous heating throughout the season from October until May. I have tried it and have found the cost to be very much higher than with intermittent heating, without any advantage from the point of view of comfort. I use a time switch arranged to cut off the heat about 6 p.m. and to switch it on again in the early hours of the morning. At the week-end the switch comes out at mid-day on Saturday and comes in again early on Monday morning, the temperature of the offices being about 60° or 61° at 9 a.m. Under the author's suggestion there would be about 37 hours of heat losses to be made good, without useful effect. The author has referred to the disability under which the engineer labours when asked to guarantee the temperature of buildings which are only in the paper stage. I agree with this and have sometimes found it necessary to make corrections of as much as 10 per cent. The only other type of electric heating of which I have had experience is the high-temperature panel system, but I find the panels rather fragile, which is not surprising when one remembers that they are slabs of fireclay about 25 in. × 15 in. × $\frac{3}{4}$ in. It would be interesting to know whether the manufacturers have tried to reinforce the panels with embedded steel strips.

Mr. A. G. Engholm: Electric heating of buildings has many advantages, especially as regards installation and manipulation. Unfortunately the price of the electricity required to give the necessary number of B.Th.U. over the normal heating period in a building increases the cost far beyond that of a steam or hot-water system. I am of opinion that the running cost of heating by electricity is about 17 times the cost of steam or hot-water heating. Gas, even if gas-fired boilers are used, is about 5 times as costly. I therefore think that at present there is a comparatively small field for large-scale heating by electricity. The author has brought one good feature—the use of electric thermostats—into prominence. These enable a mean temperature to be maintained in any part of a building, notwithstanding variations in the outside temperature. As we only require heat for our own personal comfort, it is necessary, when we set a thermostat to govern the temperature, to take into consideration the question whether manual work is being done or not. For manual work we only require a temperature of 55 to 60° F., whereas for sedentary work we require 60 to 70° F. There are many ways, however, in which electricity can be used to great advantage by heating engineers. For instance, electrically-driven pumps are now on the market which will automatically return condensed water to the boiler or hot well, so that even if the steam pressure from the boiler dies down and the steam pumps therefore fail to operate, the electrically-driven pumps can be relied upon to do their work. The same applies to electrically-driven wet vacuum pumps, which are now able to reduce the steam pressure to as low as 26 in. of vacuum, giving a temperature of 133° F. This system of steam heating can be so easily governed by electrical control, that not only can a good mean temperature be maintained in a building notwithstanding the variation of outside temperatures, but a long temperature range can be given, say 133° to 227° F., which is equal to 5 lb. per sq. in. of steam pressure. This means a big saving in fuel consumption, as on mild days it is not necessary to generate so much steam. Such a system, electrically driven and controlled, saves at least 25 per cent in fuel consumption over even the ordinary vacuum system of 10 or 12 in. Electric indicators can be installed in the engineer's office so that it is possible to see at once whether the temperatures are being maintained on any particular floor or part of a building. Unit heaters are now being largely used which consist of steam or hot-water heated gilled copper tubes, properly encased, over which air is circulated by means of a small electric motor, using only about $\frac{1}{6}$ or $\frac{1}{8}$ h.p. On the discharge side of the unit heaters deflectors are fitted one above the other; these deflect the heated air down to the floor. These unit heaters give quite a large number of B.Th.U. per hour, for a very small cost of first installation. If electric tubular heaters could be employed in place of the gilled tubes, it would probably be very advantageous, but apparently the running costs of the former are too heavy. Perhaps the author could give us some information on this point.

[The author's reply to this discussion will be found on page 211.]

Scottish Centre, at Glasgow, 8th December, 1931.

Prof. S. Parker Smith: It is a remarkably good paper. I am principally interested in the author's panel heating system. Shortly after it was first introduced I recommended it for the heating of a hospital. It was ultimately adopted, but the panels were heated by water. I should like to have seen an example of an all-electric system in use in a hospital; and if the energy rates had been a little more favourable, electricity might have been used as the heating medium. It is interesting to consider how a room can be heated by low-temperature panels in the ceiling. The only ways in which heat can be got rid of are conduction, convection, and radiation. In the case of ceiling panels one prevents the heat from being conducted away by the use of suitable insulation. Heat can therefore escape only by convection and radiation. Consider a flat plate heated on one side and suspended in air. The relative amounts of convection and radiation will depend upon the position of the plate. If the plate is so placed that convection is prevented, radiation will take place and the

temperature will rise until the rate of dissipation is equal to the heat supplied. In the case of ceiling panels convection is prevented, consequently most of the heat is dissipated by radiation. In the panel-heated room we have seen that the temperature is practically the same from ceiling to floor. Panel heating thus removes the big objection that many people have to convection heating or air-warming. Though the room should not be chilly or cold, it is unpleasant to sit in "stuffy," heated air. One objection to panel heating is the fact that the heating goes on whether the room is used or not. One does not want to push this point too far, but one of the arguments in favour of electricity for heating is the economy resulting from the fact that it can be switched off when not required. Even with panels controlled by a thermostat, and heating going on night and day for 24 hours, may not the panel system become rather expensive with the price of energy as low as ½d. per unit? For many months in the year in Glasgow heating is needed in the house in the morning and evening, but not in the middle of the day or during the night. Panel heating, however, has a big time-lag. In London and Birmingham, cities where there is an immense amount of female labour in the factories, the domestic labour question is becoming very acute and is changing current ideas. The domestic servant is vanishing, and help in the home is being given by charwomen or day girls. This fact is rapidly solving the coal problem. However charming a coal fire may be, it is a very difficult matter to keep it going without the labour necessary to look after it. From this point of view in future the competition will be not so much between coal and electricity, as between the general systems which the author has described.

Mr. D. M. Macleod: In Lanarkshire a somewhat peculiar problem is facing us at the present time. Throughout the Clyde valley there has of recent years been a complete failure of the strawberry crop, due to plant disease, with the result that the growers have been compelled to turn their attention to other sources of livelihood. A great many of them have solved the problem by going in for the culture of tomatoes. All the way up the Clyde-side one can see on every hand large areas being covered with glass-houses, a fact which indicates that a very big load will some day be offered to the supply authorities. I understand that about 60 000 tons of coal are used annually in heating these tomato houses, which present a complicated problem so far as heating is concerned. Could the author suggest any way in which the panel system might be applied to this case? Clearly the panels could not be fixed to the roofs of the glass-houses, as they would interfere with the natural lighting and heating during the day-time, and the heat losses from the panels would become excessive.

Mr. E. Seddon: I am interested in all the author says about the panel method of heating, and the few persons I have met who have actual experience of it are delighted with the results. We must not, of course, lose sight of the fact that the public will not readily accept any proposal for electric heating which involves the cutting of walls or damage to decorations, and for this reason the tubular method is the most popular of the low-temperature systems. The one drawback of low-temperature heating is the want of glow in a room. My house is fitted with tubular heating, and I have got over this difficulty of glow in my drawing-room by fitting a painted glass panel across the fireplace representing a river scene, which is well illuminated from behind and is pleasant to look upon. The tiled hearth in front is fitted with imitation grass, and flowers are arranged on this in suitable bowls. Referring generally to the subject of tubular heating, I estimate that in Edinburgh no less than 35 000 ft. of tubing has been installed for various purposes during the past few years. We have the following numbers of buildings heated by this method: 8 churches, 8 church halls, 11 large offices, 6 dance halls, and 1 cinema. I notice on page 1047 the remark that it would appear that some form of interlocking switch is required in controlling resistance-wire convectors. Reference is made in a footnote to a maid throwing bedclothes over a glowing electric fire. I do not follow the connection between these two statements, and perhaps the author will explain more fully. On page 1048 he gives the surface temperatures of tubular heaters; I find that these figures only hold good for dull tubes, and that for chromium-plated or other brightly polished surfaces the temperature would be increased by about 25 per cent. For instance, the 60-watt heater with a polished surface has a temperature of about 250° F., so that one should be careful in selecting the positions where such tubes are fitted.

Mr. S. J. Conner: I should like to ask the author how he gets over the relative-expansion difficulties associated with the paper-embedded wires.

Mr. A. W. Johnston: Is any provision made for ventilation in the ceiling-panel system? Also, what would happen if the ceiling became water-logged? Is there any danger attached to placing electrical elements in a ceiling?

Mr. R. A. Ure: With regard to electrical heating and panel heating systems, in my view a great amount of educational work is called for among architects and others. Electrical heating received a set-back a number of years ago. When the coal strike was on a number of people adopted electrical heating, but shortly after the strike was settled these people gradually went back to the older methods on account of the smaller expense of the latter. Electrical heating presents certain difficulties for the engineer contractor, as new ideas are always being put on the market and finality never seems to be reached. This means that the electrical engineer has to change his methods every five or six years, and he is therefore rather handicapped in competition with hot-water systems.

Mr. W. D. Brassington: While I think we all agree with the author that a very low unit charge must be obtained if electric heating is to be a success, I suggest that most of the electrical schemes which are considered in the first instance are turned down on the grounds of high cost of apparatus and of installation. A second point which I should like to bring to the notice of the author is that in my area the housewife is able to have a ton of coal delivered to her coal-cellar for 18s. What can the author put forward to meet this competition? In the West of Scotland area and, in fact, all over Scotland the tariffs are comparable with any in Great

Britain. We have some very low tariffs, but they are not low enough. The manufacturer should support us by providing lower-priced apparatus. Although I have installed tubular heating in a number of halls, churches, and local housing schemes (as part of the equipment provided by the town council), the apparatus is dear.

Prof. G. W. O. Howe: I feel that the main stumbling-block in the way of the adoption of the ceiling-panel scheme outlined in the paper, is its novelty. The idea of putting heating elements in the ceiling is so revolutionary that it is bound to take a long time to become familiar to people, even when we electrical engineers are convinced that it is the right thing to do. A striking example of this inherent dislike of novelty is disclosed by Mr. Seddon's description of the way in which he has tried to replace to some extent the brightness of the coal fire, by miniature gardens and sun-lit seascapes. I suppose it is the result of an inherited craving for something visibly glowing. Certainly nothing looks more cheerless and unsatisfying than an empty fire-place, however warm the room may be. One speaker has referred to architects, and they have to be reckoned with in every scientific advance that applies in any way to buildings. It has needed propaganda to educate architects in modern lighting, and at the present time they are going through a strenuous training in the application of the recent advances in our knowledge of acoustics. The paper foreshadows the possibility of revolutionary changes in the methods of heating buildings, and architects will be faced with many new problems in this connection.

Mr. D. W. Low: I am in agreement with the author that the tubular heater transmits the largest portion of its heat to the occupants of the room in the form of convection, and I do not regard his figure of 16·6 per cent radiant heat as too low. Tubular heaters well distributed round the room provide a more uniform temperature and a more economical form of heating than individual radiators or convectors, but if short lengths of tubular heaters are arranged in groups to form radiators all the advantage of tubular heaters is lost. Tubular heaters are very suitable for buildings used for certain purposes, but their use in dwelling-houses is limited owing to their unsightliness. I would not care to have my sitting-room surrounded with 2-in. pipes, and I think that the ordinary householder would have the same objection to the tubular system as he has to the exposed pipes in a hot-water central heating system. Where the panel system of heating has a great advantage over any other system is that no pipes are exposed and the architect has all the surfaces of the room at his disposal for decoration; it is not necessary to place an iron pipe or cast-iron radiator in the centre of his most cherished piece of decorative art. In a Glasgow hospital where the new wards are heated by panels in the ceiling, and the old wards by ordinary hot-water radiators, it has been found that the temperature shown by an ordinary thermometer can be at least 5 deg. F. less in the former than in the latter, with the same degree of comfort; or rather, with more comfort in the panel-heated wards, in which there is not that feeling of stuffiness often associated with rooms centrally-heated by radiators. As with tubular heating, if the panels are concentrated in a few high-temperature groups the advantages of panel heating are to a large extent lost, and the arrangement then becomes the equivalent of a high-temperature-radiator system. I think that in the future the heating of large buildings will be done by low-temperature ceiling panels with thermostatic control. Whether it will be done by electric panels or by pipes fitted in the ceiling through which water is circulated from thermal-storage tanks, will depend upon the electricity supply authorities, as the rates must be such as to give the heating engineer a chance of having his scheme considered. Realizing that the heat equivalents of coal and electricity do not constitute the only factor in the case, but that other important points have to be taken into account, we must regard electric heating as an alternative to the more common methods of heating by coal, gas, or oil. In view of the large amount of money a fog in a city like Glasgow costs the community, even after allowing for the extra lighting load obtained by the electricity department, I think that there is a large balance which should go to give reasonably low tariffs for electric heating. The question of tariffs for electric heating should be given immediate and careful consideration by all supply authorities, so that heating engineers may be in a position to know what the heating tariffs are and be ready with their schemes at the right time. Otherwise, they may find that, owing to delay in arranging tariffs, more chimneys will be erected, thus making the smoke problem even graver than it is at present. Have the fire-insurance companies approved low-temperature electric panels in the form of bare wires between what appear to be two sheets of press-spahn pressed together and fixed to the ceiling like a ceiling paper?

[The author's reply to this discussion will be found on page 211.]

Western Centre, at Bristol, 14th December, 1931.

Mr. W. A. H. Parker: The author's figure of 2 000 units per annum to cover the average consumption of electricity for the heating of a room in a house seems to me to be on the high side. I am interested in a house where most of the heating is done by tubular heaters and a certain amount of radiant heat is also employed; last year the total consumption of this installation worked out at just over 1 000 units per room. The author makes a very important point when he mentions that thermostatic control of these systems is essential. I believe it would pay to install a thermostat in each room of the house or office. Under ordinary circumstances 55° F. is sufficient in the average home, but in offices it may be necessary to keep the temperature higher because of the lack of movement of the occupants when working. I was sorry to hear previous speakers decrying the use of electricity for heating, as I believe that there is quite a lot of business obtainable in this direction with the price of electricity at about ½d. per unit. We ourselves have experience of a large office

panels being reflected to the floor. This has been refuted in a previous discussion*, and it would therefore appear that the saving in current compared with, say, tubular heaters under windows, must be at the expense of cold draughts at these points. In Appendices III and IV the actual consumption of a given installation is shown as being only one-third of the estimated consumption. While this discrepancy may to some extent be accounted for by casual heat, it suggests that the calculations may also be faulty. Mr. A. H. Barker's recent paper† stated that the art of radiant heating was to-day in the same state as convection heating was 30 or 40 years ago, and while appreciating the endeavours of the author and Mr. Barker to put the subject on a scientific basis, we are at liberty to feel that at present the claims made must be accepted with some reserve. It seems to me that a combination of heating methods will be found to be most effective in the long run. With regard to the author's advocacy of continuous heating, this question surely depends on the use to which the building is put. Presumably he would not advocate the continuous heating of churches, and as schools are used only for 40 hours a week, why heat them for 168? The temperature of the rooms can be raised to the required value in two or three hours at most, and even if the running hours are thereby increased by 50 per cent they are still only 40 per cent of the possible number. At the discussion before the Institution‡ Dr. Ekstrom confirmed this by giving figures from tests in which a 40 per cent saving in consumption was obtained by switching off from 5 p.m. to 7 a.m. Provided that the supply authorities do not insist on a 24-hour load for a heating rate of 1d. or less per unit, there appears to be no reason for the additional consumption. I fully endorse the claim made by the author that electric heating is usually in every way an economical proposition, and is undoubtedly the most efficient. But, I agree, thermostatic control is essential.

Mr. W. Moffat: I should be glad if the author would state at what surface temperature the low-temperature radiant panels would work when embedded in plaster. In view of the fact that they are embedded behind plaster and any renewals would mean cutting away a portion of the ceiling, it would be interesting to know the life of the panels. As regards floor heating, Liverpool Cathedral is heated in this way by an installation designed by the firm with which I am connected. The temperature a few inches from the floor is 60° F. and 100 ft. above the floor-level it is 58½° F.; the temperature at the floor itself does not exceed 72° F. The uniformity displayed by these figures appears to be an argument for floor as opposed to ceiling radiant heating.

Mr. W. Hill: With regard to ripple control, is the author of the opinion that this system will operate satisfactorily when all the supply authorities are connected to the "grid"? It seems to me that we might easily get our mains overcrowded with ripples in the same way as the atmosphere has become overcrowded with wireless waves. I should be glad of some further particulars of the ceiling-paper panel, as it seems to be a very cheap and simple form with which the uninitiated may make experiments.

[The author's reply to this discussion will be found on page 211.]

Mr. F. S. Grogan: In my opinion the author is not entirely impartial when comparing the merits of the various systems of electrical heating. He is certainly unjust to the heating of buildings by electric fires and tubular heating systems, and he rather overstates the case for low-temperature panel systems. I have summarized Table 4, taking the higher value where two are given, and have allocated to the A, B, C, and D classifications marks of 4, 3, 2, and 1 respectively. The results are: low-temperature embedded ceiling panels 41 marks; radiant lamp heaters 36; and electric fires, tubular heaters, and high-temperature panels all equal at 33. The author awards too many "A's" to low-temperature panel heating. His results are quite wrong for radiant lamp heaters, which are now almost entirely superseded by electric fires and tubular heating. There are many thousands of electric-fire and tubular-heating installations operating to-day to the entire satisfaction of the user from every aspect. Their capital and maintenance costs are small, and running charges are low where the electricity supply tariff is favourable. Flexible cords should not fail at the point of entry if suitable terminals are arranged. For such connections I have recently employed enamelled wire suitably insulated with braided and impregnated asbestos. Reference is made to the possibility of the heating coils in tubular heaters making contact with the metal wall of the tube. My comment upon this is that if proper methods of construction are adopted it is impossible for the heating element to burn out under any practical conditions. I have here a section cut from a 10-ft. length of tubular heater; the resistance wire is of the same composition as that used in an electric fire operating at 1 800° F., and normally when loaded to 66 watts per foot run the resistance wire is only at a black heat. I cannot see how such a construction could deteriorate even after 50 years' service, and in any case every tubular heater throughout the system should be efficiently earthed. Referring to Fig. 2, I must take exception to the statement that the inverse-square law only applies to radiant emissions from a point source. As the panels cover a comparatively small area compared with the total floor area, the intensity of the radiant energy must decrease approximately as the square of the distance from the source. The early experiments of Tyndall showed that the most intense heat is not found in the most luminous portion of the spectrum. A body at low temperature, say less than the boiling point of water, emits non-luminous radiation. This emission of dark heat increases very rapidly with small rises in the temperature of the heated body. For instance, if the heated body is made of iron, upon reaching a full red heat it will throw out 27 times the radiant heat emitted at a low temperature,

* See Mr. HALLETT's remarks on page 1099 (vol. 69).
† "The Principles of Calculation of Low Temperature Radiant Heating," *Heating and Ventilating Engineer*, 1932, vol. 5, p. 246.
‡ *Journal I.E.E.*, 1931, vol. 69, p. 1096.

and when approaching an orange temperature 60 times. The majority of this heat radiation is beyond the range of the visible spectrum. In other words, the higher the temperature of the heating source the greater is the proportion of radiant energy emitted compared with the heat conducted away. In all conversions of electrical energy to heat energy the efficiency is 100 per cent, but a very marked difference is obtainable according to the design of the heating apparatus and the resulting surface temperatures which heat the building. The author makes a great claim, especially in Fig. 19, for panel heating by radiant heat, and I should like to know how he can justify this claim in the face of scientific records which show that only a small percentage of the total energy can be emitted as radiant heat. Some years ago I proved in practice that the substitution of a $2\frac{1}{2}$-kW fire having a 70 per cent output of radiant heat saved for the electricity supply undertaking a heating consumer who would otherwise have ceased to take electricity for heating purposes through an older type of electric fire consuming 3 kW. Later experience has proved to me that the loading with a tubular heating system can be some 25 per cent lower than would be installed for electric fires in the same room. The chief difference is that in cold weather at least an hour must be allowed for the tubular heating system to bring the temperature of the room to a satisfactory figure, whereas in the case of electric fires the sensation of warmth experienced when switching on is almost instantaneous because of the amount of heat thrown off as radiant energy. It is well known that glass will absorb heat radiated from low-temperature bodies and will transmit some of the radiant energy emitted from heating sources at luminous temperature, but this cannot altogether account for the extravagant claims in favour of panel heating, because it is not necessarily only high-temperature radiation which is associated with the electric fire. While a very small proportion direct from the source may radiate through the glass, the majority strikes the walls, furniture, and people in the room, and is then converted into heat and radiated away from these bodies at low temperature. This picture of the distribution of heat from an electric fire explains why in large buildings where numbers of people congregate another system of heating is necessary. For such buildings I have found the tubular heating system effective and economical, provided thermostatic control is employed. Under ordinary conditions a fair estimate of the annual consumption is provided by taking one-third of the working hours during the heating season operating at full load.

Source	Temperature of source	Watts per sq. ft. of heating surface	Number of sq. ft. of heating surface per kW	Capital cost per kW
	°F.			shillings
Electric fire	1 800	5 500	0·18	10 to 70 (approx.)
High-temperature non-embedded panels	500 to 550	550	1·8	65
Tubular heaters	200 to 250	115 to 200	5 to 9	44
Low-temperature non-embedded panel..	100 to 150	80	12·5	200
Low-temperature embedded panel ..	80 to 85 (nominal), and up to 120	25 to 30	40	—

I maintain—in spite of the author's recommendation of continuous heating over the 24 hours—that this is the more economical procedure, because it eliminates the heat losses during the night, which obviously are higher than during the day. Such an estimate of the loading of the tubular heating system should be based strictly on the heat losses of the building in question, and not upon the rule-of-thumb process of allowing a fixed number of watts per cub. ft. As the author shows in some cases, the watts per cub. ft. may be quite a small fraction of unity, whereas in other cases, such as an up-to-date school with ample glass area on both sides, the watts per cub. ft. often amount to as high a figure as 1·6. For such a school the consumption should probably be based on from 50 to 55 per cent of the working hours operating at full load. For large buildings equipped with ceiling-panel heating systems the author claims a very low figure of watts per cub. ft., if thermostatically-controlled continuous heating night and day over the heating season is adopted. Much greater loadings on other systems will produce almost a 50 per cent saving in annual running cost, however, as I hope to show later. Over the last 18 weeks two similar sets of rooms in a school of the type to which I have referred have been tested for consumption figures as between the high-temperature panel and the tubular heating systems. Over part of the period there was little difference in the units consumed, but up to date there is a slight difference in favour of high-temperature panel heating. Referring to Table 7, I do not think that even for the purpose of calculation the author should deliberately reduce his loading for the room in question by taking only 25 per cent of the full air losses. If the room is to be properly heated and ventilated the air losses must be identical in the two cases. If he can establish his facts, however, the economy in loading should be taken as a percentage off the total heat losses. I have no experience of the radiation thermostat, but for general purposes I should prefer the ordinary thermostat operated by the temperature of the room. Turning to Appendix II, the fact that the maximum load is only 8 kW for a connected load of 20 kW suggests that a loading of about 15 kW would be ample, and for such a block of offices full load for one-third of the working hours (i.e. 10 hours per day for 212 days) would give a consumption of 10 600 units, which is $33\frac{1}{3}$ per cent less than the units shown for the 24-hour method. Referring to Appendix VI, the figures given in the last column are very much open to question; the variation being so vast, they can serve no useful purpose. If the operating costs shown in Appendix VII

represent continuous heating over the 24 hours, it helps me to prove that in spite of the low figure of watts installed the consumption is excessive. If tubular heaters loaded to 1 800 watts had been installed, the daily consumption for a 30-deg. rise—even if we allow 14 hours per day for a dining-room, which is on the high side—would be $(1{\cdot}8 \text{ kW} \times 14) \div 3 = 8{\cdot}4$ units per day, against the author's average figure of 15·9. The approximate figures given in the table on page 1062 show that the capital cost per kW installed must grow to a very high figure if excessively low temperatures are to be employed at the heating source. According to Appendix IX, the fixing of panels in the ceiling costs £18 per kW, as against which figure the installation of tubular heating costs only about £4 per kW, including the wiring and switchgear. I think the author has failed to establish his point that low-temperature panel heating is much more economical than tubular heating. Tests made by the late Mr. Dowsing 20 years ago showed that whilst non-luminous heaters gave a normal temperature up to 5 or 6 ft. from the ground-level, temperatures of the order of 70° F. were obtained at the ceiling-level. Why, therefore, go to the expense of ceiling-panel heating when by the installation of tubular heaters at correct surface temperatures and suitably placed we can get the whole of the ceiling to operate as a low-temperature panel heater at a greatly reduced cost?

Mr. W. L. Webb: I am glad to find that the author favours luminous radiators. In my own house I have a luminous lamp radiator with three lamps and a 3-kW heater, which I find very satisfactory; in the summer the luminous lamp radiators are used alone, and in the winter months additional heat is obtained from the radiator bars. As regards thermostatic heating of rooms, one maker advocates putting the thermostat near the door, and another putting it where the heat is emitted. I noticed recently that thermostats were placed at the entrance of a picture gallery and there was a great variation of temperature in the building. It would be interesting to know the number of thermostats one should use for a room of large cubic content, and also the correct position for these. Regarding radiant heat, in the arboretum at Derby there is an open-air aviary in which the mortality of the birds was very high due to the cold nights. We fixed at the back of the perches a luminous heating panel the dimensions of which were about 3 ft. × 1 ft., and since this was done none of the birds has died.

Mr. W. F. Furse: So far the paper has been criticized from the point of view of men interested in different systems of heating, rather than from that of the question whether there is a big field for electrical heating. The advocate of thermal storage says that, irrespective of the inefficiency resulting from the loss of heat in the pipes, he can heat a building cheaper because he can take the current at off-peak load prices. The tubular-heating and radiator enthusiast says that the author must have an insulated house for the panel-heating system before if it is to be at all efficient. The supply engineer maintains that if he has to buy electricity from the "grid" at £3 10s. to £4 per kW and 0·25d. per unit, he is bound to lose money on a building which is heated by panels. Undoubtedly low-temperature embedded-panel heating from hot-water installations fired by oil fuel has made great strides, and must therefore have considerable merit. Has the author any comparative costs of heating a building with low-temperature panel heating by hot water, and low-temperature panel heating by electricity? He points out the well-known fact that the thermostat which he is using is suitable only for a.c. circuits, but I should be glad to know what alternative he would put forward in the case of a d.c. supply.

Mr. J. F. Driver: Some years ago tubular heating was installed in eight classrooms at the College, Loughborough, and the installation has been a great success. We are now equipping a hall of residence for 90 students as an all-electric building. All the rooms of this building are electrically heated, and cooking and water heating will be done by electricity. The total load will be of the order of 400 kW. I am particularly interested, therefore, in the "electric ceiling paper" described by the author. If low-temperature panels are used, is it necessary to switch on a long time before the room is occupied? I have at home a room which is heated by tubular heaters, with a radiant fire for boosting; even when the outside temperature is very low the room becomes comfortably warm within 10 minutes of switching on. While I appreciate that gradual heating is satisfactory where rooms are used every day, in the average house there are "casual" rooms where heat is only required at week-ends or at irregular intervals. In such rooms it is desirable to be able to produce comfortable conditions quickly. From long personal experience I can say that in clean houses where a vacuum cleaner is regularly employed, tubular heaters do not blacken the walls with dust. The author appears to get a good efficiency with his panel heating by stuffing up all the cracks in the room and reducing the number of air changes. I cannot agree to this. A great advantage of ceiling heating is undoubtedly the fact that it does not interfere with furniture and involves no danger of scorching fabrics. Will the author give his views regarding the suggestion to fix tubular heaters at picture-rail height? By fitting "dummies" it should be possible to make the tubes harmonize with the general scheme of decoration.

Mr. L. M. Jockel: I strongly support the author on the question of tariffs (page 1046, vol. 69). Forty years ago the late Dr. Hopkinson showed that electricity should be charged for on a 2-part tariff, but possibly, like the late Dr. Ferranti, Hopkinson was about forty years in advance of his time. Engineers have in the interval developed complicated scientific methods of charging, whereas if development is to proceed rapidly it is essential that simple and easily-understood 2-part tariffs should be adopted. Recently I had to install an electrical heating system in two offices heated by coal fires but having electric fires for occasional use. I decided to install tubular convection heaters with a loading of 60 watts per ft., and with the existing electric fires a total loading of 1·40 watts per cub. ft. of space was obtained. This figure seems to be rather high, but it has given satisfaction, and I should like to ask whether the figure of ½ watt per cub. ft. of space which the author quotes is not too low in general practice with

thermostatic control. I suggest that about 1 watt per cub. ft. of space is safer, although I know how difficult it is in heating work to decide on a definite figure applicable to all cases. The author mentions the triple-tariff meter of the Compagnie Parisienne de Distribution d'Électricité, and I should welcome further information regarding triple tariffs, as they might be useful as a temporary measure until British supply engineers are able to agree on some simpler form of tariff.

Mr. B. Gill: I should like to support the author's claims regarding the superiority of the low-temperature ceiling-panel system of electrical heating. A good electrical heating installation offers a much higher standard of comfort than that provided by other types of heating systems, due to the even temperature control which it provides. At ½d. per unit the cost of heating a house in this way is not more than £3 to £4 greater than that of heating by coal. After my experience of low-temperature electrical heating I would never go back to coal-heated rooms if cheap electricity were available.

Mr. D. M. Duncan: I disagree with the author regarding the relative merits of continuous and intermittent heating (page 1059, vol. 69). He infers that once the building has been heated up only a few units per day are required to maintain the desired temperature. In his analogy of the loaded truck he loses sight of the fact that more energy is required to push the truck up a hill than along the level; in the case of the heating installation this means that the system must be capable of heating the building on a sudden cold day, when more heat units than usual would necessarily be required. The heat losses through walls, glass, etc., vary with changes in the outside temperature. Although the weekly consumption varies owing to outside temperature changes, the author's theory does not apply in one single instance to the guaranteed figures for the running costs of tubular and other systems of electrical heating to which I have access. In his analogy he may be referring to buildings specially insulated with a 3-in. layer of cork, but such buildings are very hard to find. If I informed a prospective consumer that after first heating up the building only a few units per day would be required to keep the cold away, after a year's working of the installation I should probably have to meet a very enraged consumer. In many cases it is impossible to use panel heating with success. For instance, where one requires heat for the total volume of a building with guaranteed variations of ± 1 deg. F. at 70° F. to enable expensive machinery to operate with success, the radiant method would be useless owing to the fact that it would give rise to "hot spots." I have experienced inferior heating with ceiling panels owing to a restricted area only being heated; outside that area conditions are very uncomfortable in such cases. My experience of many forms of heating inclines me to the view that a high efficiency is obtained with the tubular system combined with a modified form of panel heating. A system which is satisfactory when applied to one particular building may be a failure when installed in another. The capital cost of panel heating is 3 to 4 times that of tubular heating, but when combined the two systems give good results.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT NEWCASTLE, LEEDS, BIRMINGHAM, GLASGOW, BRISTOL, AND LOUGHBOROUGH.

NEWCASTLE.

Mr. R. Grierson (*in reply*): In reply to Mr. Jewsbury, we have obtained very satisfactory results with the "Satchwell" thermostat in rooms warmed by the low-temperature ceiling-panel system. In actual practice a room "constant" is obtained which connects the condition of comfort with a definite setting of the thermostat. It is possible that the eupatheostat type of thermostat may maintain conditions slightly more perfect than those obtained with the Satchwell thermostat, but they introduce the complication of relays and additional wiring, they are more costly to install, and their ability to maintain a condition of comfort remains to be proved. Regarding the figures given in Appendix X, I note that Mr. Jewsbury questions the costs of the hot-water panel thermal-storage system, but he does not put forward alternative figures.

I think it will be generally agreed that Mr. Clothier's contribution to the discussion is a most valuable and helpful one. The collection and publication of really reliable data relating to consumption and cost are of vital importance to the industry, and I am hopeful that either the Institution, the Electricity Commission, or the British Electrical Development Association will take this task in hand immediately. Architects and consumers all appreciate the advantage of "doing it electrically," and fear of the cost is the obstacle to be removed before marked progress can be made with domestic electric heating work. In regard to the value of the heating load, I would refer Mr. Clothier to Figs. G, H, and J in my reply. Mr. Clothier examines the multiple-earthing problem at some length, and then arrives at the conclusion mentioned by me on page 1051 (vol. 69). Regulations are only made to prevent abuse and danger, and I feel that the time is ripe for the Electricity Commission to review the Regulations concerned. If they are satisfied that the risk of danger is negligible, then these restrictions should be removed forthwith.

I cannot understand Mr. Carr's reason for opening his remarks on the pessimistic note, and reminding us that the efficiency of the turbo-alternator is 24·5 per cent. The other aspect of the situation is equally true and very much more to the point, i.e. that the cost of good house coal is 48s. per ton in the London suburbs, that space is required to house it, and that labour is required to transport it from the coal store to the coal scuttle and eventually to the fire. Ashes require to be removed, grates to be cleaned, chimneys to be swept, and rooms to be dusted. Has not Dr. Margaret Fishenden shown* that the radiant efficiency of the coal fire is from 17·5 to 25 per cent, that direct convection heating accounts for less than 5 per cent, and that these values indicate

* See Bibliography (3).

an aggregate efficiency of from 22·5 to 30 per cent? On the other side of the picture, I am informed that a reasonable price for the coal burnt by the average power station is approximately 17s. per ton delivered in the furnaces. It should be unnecessary for me to labour the point further in order to indicate the possibilities of electric heating under thermostatic control. In requesting me to give values for the normal window area for the control room of a power station, I think Mr. Carr has overlooked the fact that the paper purports to deal with the electrical heating of buildings and not with the architectural design of power houses. Regarding the method of calculating the heat losses for any given building, I was hopeful that I had indicated my views on this aspect of the subject in paragraph 8 of Section (2), in Tables 7 and 8, and in Appendices VIII, IX, and XI of the paper. If I were calculating the heat loss of the building in question, I should figure the heat losses on the basis of an air change equal to 50 per cent of the cubic content for a low-temperature ceiling-panel system, and for an air change equal to twice the cubic content for a convection system. It should be clearly noted that whichever system is adopted, *the natural air change would be in no way interfered with*, and entirely depends on the method of construction, aspect, workmanship, etc. Unfortunately Mr. Carr has omitted to state the thickness of the exposed wall, the temperature maintained on the other side of the interior wall, the

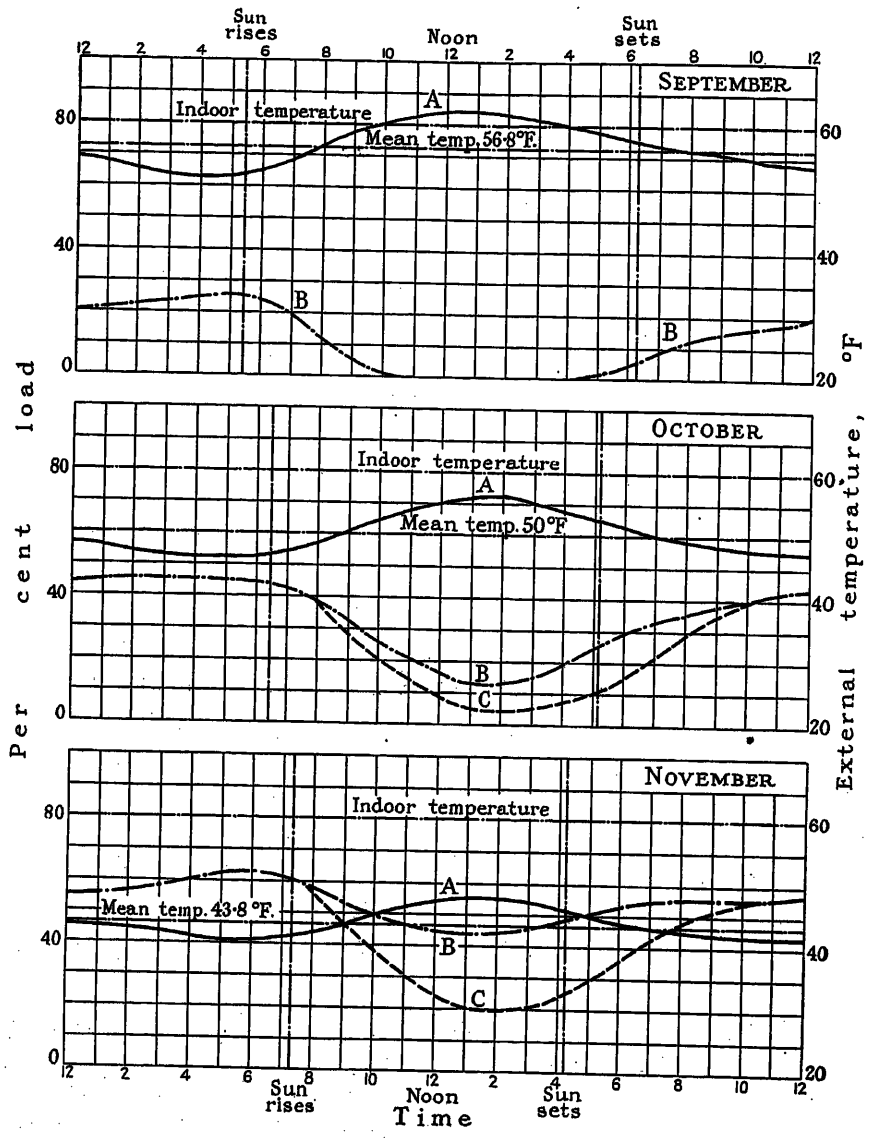


FIG. G.—Graphs showing hourly variation of the outdoor temperature and the corresponding heating load. (See also pages 1069, 1070, and 1071, and Figs. 15 and 17, for the effect of casual heat in flattening the total-load curve.)

Curve A:—Mean outdoor temperature. Curve B:—Theoretical load (as percentage of kW) to maintain 60° F. indoors. Curve C:—Estimated load (as percentage of kW) allowing for casual heat, but excluding the effect of thermal storage of the structure. (See also page 216, col. 2, for method of construction.)

type of floor construction, and whether it is on the earth or if there is a warm or cold basement below it, details of the ceiling construction, and whether there is a warm or cold room over or whether it has a flat roof, and if the latter, whether it is insulated. Mr. Carr states that he has obtained the loading of 58·8 kW by employing the constants given on page 1088 (vol. 69). Had Mr. Carr studied the details of construction of the room in question (given on page 1087, vol. 69) he would have seen that the exterior walls are 9 in. brick, the interior walls are 4½ in. brick, the floor is 1 in. boards on joists, the ceiling is lath and plaster on wood joists, and the total content is 1 536 cub. ft. Such construction would scarcely be suitable for the volume of 98 000 cub. ft. mentioned by Mr. Carr, and the constants naturally vary. If he will forward me a plan of the building I will have the heat losses communicated to him.

Mr. Richardson is also in pessimistic mood without disclosing any good cause or reason. He complains that I have avoided any detailed comparisons, but I feel that my reply to Mr. Carr justifies the course I have adopted. As I stated in my reply to Mr. Skinner, my object in writing the paper was to indicate the very large market available for the sale of current, and in my reply to Mr. Fraser I have stated that my object was to induce all electrical engineers to try out for themselves the modern types of thermostatically controlled equipment. I cannot but feel that it is early days to

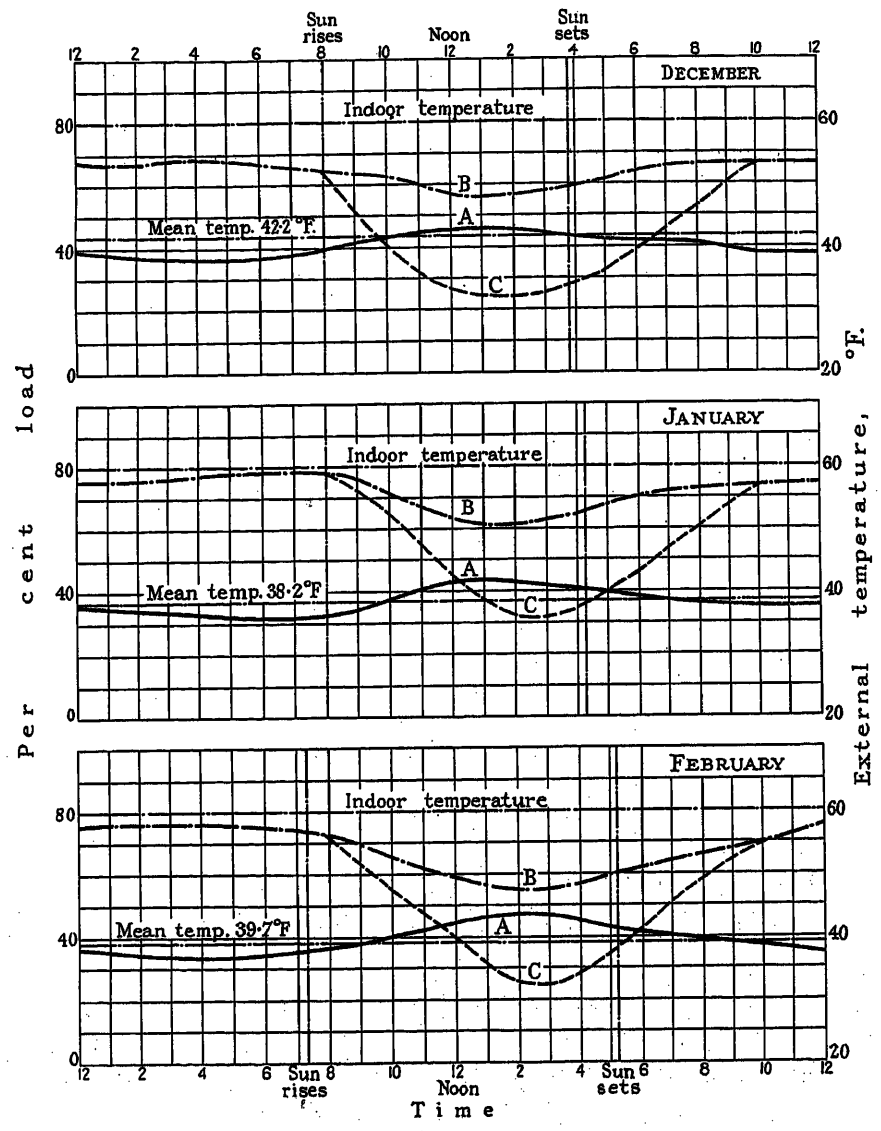


FIG. H.—Graphs showing hourly variation of the outdoor temperature and the corresponding heating load. (See also pages 1069, 1070, and 1071, and Figs. 15 and 17, for the effect of casual heat in flattening the total-load curve.)

Curve A:—Mean outdoor temperature. Curve B:—Theoretical load (as percentage of kW) to maintain 60°F. indoors. Curve C:—Estimated load (as percentage of kW) allowing for casual heat, but excluding the effect of thermal storage of the structure.
(See also page 216, col. 2, for method of construction.)

endeavour to decide the argument of the thermal storage versus the direct system, because the former is most definitely in the experimental stage, and I am informed that one firm lost several thousand pounds on one installation alone. Clearly the cost of such an installation is not the contract price but the actual cost to the contractor, for repeat orders would not be taken at the same price. On the other hand, if experience shows that mass production of the boilers and all the automatic gear can be proceeded with, then the cost of the thermal-storage system may fall considerably. Mr. Richardson also mentions the possibility of controlling the temperature of the whole building from one room which can be regarded as an index room. From my fairly extensive experience of this aspect of the problem, I have no hesitation in stating that there is no index room in any building, and I would point out, once again, that each degree Fahrenheit maintained in excess of the desired temperature represents an addition of 5 per cent to the cost of energy, for so long as it is maintained. I would also refer Mr. Richardson to Table 10 (page 1068) to indicate the difficulties experienced in finding the " central room " to which he refers.

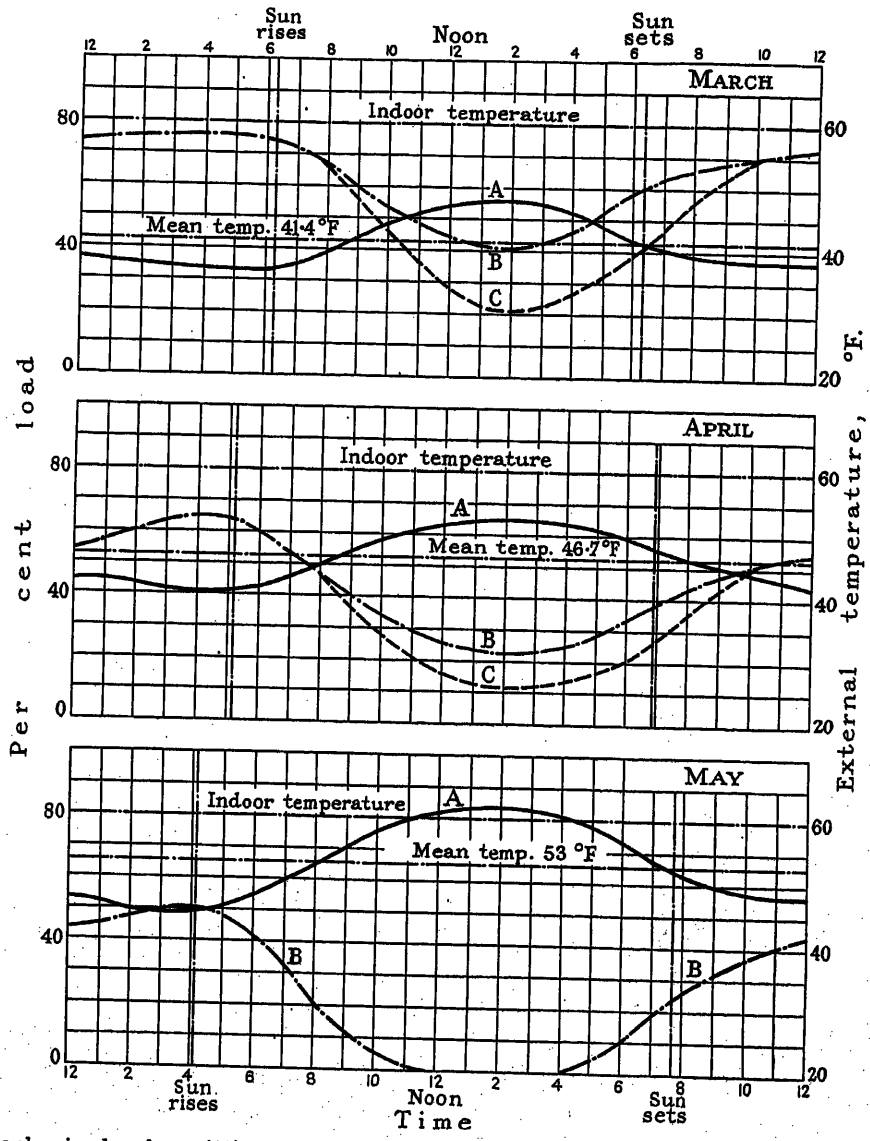


FIG. J.—Graphs showing hourly variation of the outdoor temperature and the corresponding heating load. (See also pages 1069, 1070, and 1071, and Figs. 15 and 17, for the effect of casual heat in flattening the total-load curve.)

Curve A:—Mean outdoor temperature. Curve B:—Theoretical load (as percentage of kW) to maintain 60° F. indoors. Curve C:—Estimated load (as percentage of kW) allowing for casual heat, but excluding the effect of thermal storage of the structure.
(See also page 216, col. 2, for method of construction.)

Mr. Carter has analysed the operating principle of the Satchwell thermostat on a.c. circuits. The important principle is that the contact lever is practically in an unstable state of equilibrium and merely has to topple over to make and to break alternating currents of the

order of 10 to 15 amperes at 230 volts, so that the operating force required is exceedingly small, and the accuracy is relatively high. The small travel necessary to effect the "make" and break is also an immense advantage in securing close differentials.

LEEDS.

I would agree with Mr. Skinner when he expresses his preference for high radiant temperatures and low air temperatures, if such a condition could be proved to be practicable. The only method whereby such a condition can be provided is to remove the whole of the convected heat that is produced, and, as Dr. Parker Smith has shown,* the radiant efficiency of the electric fire averages 65 per cent. The other objection is the difficulty experienced in efficiently warming the *entire* floor area by means of high-temperature radiant sources. Heat shadows are formed, and the inverse-square law is effective to a very marked extent, with the result that the only comfortable area of the room is that included in what I have termed the "magic circle." In other words, it is necessary to "sit round the fire." If Mr. Skinner proceeds with his experiments with the bowl fires fixed near the ceiling, he will observe the formation of the well-known convection dust patches—inseparable from all forms of convection warming—on the ceiling, and he will find that the cost of maintaining a white ceiling is excessive. Again, if in the larger rooms several fires are distributed about the room, in order to eliminate the heat shadows, and so to secure a moderately even distribution of the radiant warmth, it will be found that the loading is out of all proportion to the cubic content. One further objection is the feeling of nausea produced when high-temperature radiant-heat rays are allowed to play on the back of the body. The rays penetrate the clothing quite readily, and experience has proved that it is not possible to sit, with any degree of comfort and for any length of time, within a distance of 6 ft. of a wall panel operating at a temperature even as low as 100° F. The figures given in Appendices V and VI are for net cubic content, i.e. the net internal dimensions of the warmed space. Those who have had experience of intermittent and of thermostatically-controlled continuously-warmed rooms will agree that the former method merely mitigates the sense of discomfort, while the latter, if the installation is skilfully planned and controlled, provides a sense of comfort that must be experienced to be appreciated. Mr. Skinner attempts to compare the cost of energy for an intermittent type of heating installation with the cost of energy for a continuous, thermostatically-controlled type of installation, to the detriment of the latter. In doing so he has overlooked the fundamental law of experimental work, which is to remove all but one variable quantity. The parallel case is the comparison of the cost of living of the poverty-stricken man and of the man in receipt of a comfortable income. The former may regard an annual food bill of from £25 to £50 as being satisfactory, while the latter would maintain that he could not exist on anything under £250 to £500, yet they may both be of the same weight and height. Both men would be right, they merely differ in their point of view regarding cost, quantity, and quality of food. Mr. Skinner has employed the figures contained in Appendices V and VI in a way that I did not intend them to be employed. My object in publishing these figures was to indicate the very large market available for the sale of current and, moreover, the sale of current in comparatively large blocks. His conclusions, however, coincide with the views that are beginning to form in my own mind, i.e. that, to be comparable, all items being taken into account, the restricted-hour rate for thermal-storage systems must be of the order of 25 to 33 per cent of the "on tap" rate.

The experimental results obtained by Mr. Wilkinson regarding air and radiant room temperatures for an equal degree of comfort coincide with the views now very generally accepted. Mr. A. H. Barker* has attempted to tabulate these values in the following way:—

RADIANT AND AIR TEMPERATURES.

Radiant temperature, ° F.	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80
Air temperature, ° F.	72	70	67	65	62	60	58	55	53	51	46	45	43	40	38

I think that Mr. Wilkinson has drawn the wrong conclusion when he refers to a loading of 230 kW in a church. Such a case is exceptional and is solely due to the intermittent form of heating that has been adopted for the building in question. The parallel case is the very large water tank that is only used occasionally. The tariff offered induces the consumer to fill it in the minimum of time, just before it is required for use, so that very large pipes are necessary. If the tank is reasonably free from leakage, the time of filling could conveniently be arranged to occupy a much longer period, and the leakage to be made good would call for a much smaller pipe. Mr. Wilkinson describes experiments with cast iron as a medium for thermal storage, but the heat emitted must be almost entirely of the convected type, and the equipment must be bulky and of considerable weight, so that its application must be restricted to a marked extent. Similar appliances based on the use of (I think) soapstone and similar minerals have also been described.

Mr. Fraser is on very sound ground when he advises progress with caution. My object has been to induce all electrical engineers to abandon the old and entirely incorrect ideas regarding the relative costs of heating by coal, coke, gas, oil, and electricity—based solely on

* "The Radiant Efficiency and Heat Distribution of Electric Fires," *Journal I.E.E.*, 1930, vol. 68, p. 1211.

* "The Principles of Calculation of Low-Temperature Radiant Heating," *Transactions of the Institution of Heating and Ventilating Engineers*, 1931, vol. 30.

the calorific values and on the costs of the raw materials —and to try out for themselves the modern types of thermostatically controlled electrical heating equipment. If we can only convince ourselves first, we shall experience very little trouble in convincing the general public regarding the commercial practicability of electrical heating. They appreciate the advantages, and the fear of the operating cost is the only obstacle that remains to be surmounted. The heavy loadings of the type of installation to which Mr. Fraser refers will prove difficult to handle in many areas of supply where good progress has been made with electric cooking, as the first cooking peak occurs between 7 a.m. and 9 a.m. There is no question at all that tens of millions of units could be sold for the purpose of warming elementary schools, and there is no question that this is an attractive load, as the thermal-storage capacity of the structure and the contents, and the casual heat of the occupants, permit the current to be switched off 1 to 2 hours before the school closing time. When travelling down from Scotland recently the steam-heating pipe coupling between the second and third coaches blew out just after leaving Carlisle. Although the outdoor temperature was 38° F. the temperature in the train was well maintained until we reached Crewe 3 hours later. This is an interesting and unexpected proof of the thermal-storage capacity of a structure, and the effect of casual heat and insulation, in maintaining the desired temperature.

I am not convinced that humidity has the effect on comfort that Mr. Logan suggests, and unfortunately he has not included figures either for the relative humidity or for the wet-bulb readings, taken during the periods to which he refers. Personal observation indicates that the relative humidity indoors is remarkably constant in continuously warmed and adequately ventilated buildings, notwithstanding considerable variations in the outdoor conditions. I am inclined to question the temperature actually maintained in the room referred to by Mr. Logan, or possibly the location of the panel surface in relation to the exposed surfaces of the structure—in other words, whether the radiant "coldth" was adequately negatived or compensated for. In the event of Mr. Logan's contention being proved to be correct, with a thermostatically controlled system it is a simple matter to set the room thermostat up 2 or 3 degrees during the prevalence of the unusual conditions. Mr. Logan's reference to the coat-drying—or rather, the non-drying—episode is interesting. If he observes a pavement on a damp day he will note that it remains damp so long as the sun is obscured by clouds. Immediately the first ray of sunshine breaks through the clouds, the pavement dries as though by magic—owing to the radiant heat of the sun. Mains engineers have also for many years been acquainted with the effect of fault currents and of the resultant soil heating on pavement drying, but have probably not realized the fact that the phenomenon is simply one aspect of low-temperature panel heating. So far, no labour difficulties have been experienced in connection with the new forms of heating equipment, and none is contemplated. The erection of a lift is an example of work by a composite tradesman. He fixes the steel guides, puts the car together, lifts the engine into position, and wires up the controller. The new thin "Dulrae" is ignitable when it is isolated in air, but when it is fixed to a plaster ceiling or to a cement-asbestos board it can be regarded as non-ignitable, because the access of air, which is required for ready combustion, is restricted. The application of a blow-lamp to the finished ceiling will char a hole in the material but general ignition will not ensue. I have no information which would indicate that exposure to high-temperature ceiling panels may cause a condition approximating to sunstroke, but from experiments that I have carried out with both types I find the low-temperature type preferable (see also my reply to Mr. Skinner). Following Mr. Fraser's reference to Fig. 15, and in order to explore further the inversion of the ordinary load curve, I have prepared the graphs shown in Figs. G, H, and J from the data given in Table 5 (page 1061, vol. 69), for the months of September to May, inclusive. Graph A shows the hourly variation in the outdoor temperature from midnight to midnight, while graph B represents the *theoretical* heating load curve of a dark and empty shed constructed of thin sheet metal (i.e. a structure having no casual heat, no thermal-storage capacity, and maximum heat transmission through the walls). The data for the graph have been calculated by ascertaining the difference between the outdoor temperature (at the various hours) and the assumed indoor temperature of 60° F., this being a mean of 63° or 65° F. for sitting-rooms, offices, etc., and 55° F. for corridors, bedrooms, etc. It has then been assumed that the average heating installation will be designed for a 30-deg. F. rise of temperature (30° to 60° F.), and the *difference* between the assumed indoor temperature and the actual outdoor temperature has been plotted as a percentage of 30° F. Thus, from Table 5, the outdoor temperature on September 1st, between the hours of midnight and 1 a.m., is 54° F., or 6 deg. F. below the desired indoor temperature of 60° F., so that the *theoretical* heating load is 6/30ths or 20 per cent of the maximum. This value of 20 per cent is therefore plotted on the midnight ordinate. In the graphs for October to April inclusive I have introduced a third curve (C), which is an attempt—and only an attempt—to indicate the effect of casual heat introduced by the occupants of the rooms, artificial lighting, the radiant heat of the sun, cooking, hot water, etc. In other words, graph C purports to show the probable shape of the heating load of the individual building, allowing for casual heat, but there still remains to be considered the effect of the thermal-storage capacity of the structure and the contents, and also the diversity created by the operation of thousands of thermostats controlling loads of the order of from 1 to 3 kW.

I note that Mr. Longman is intrigued with the possibilities of thermal storage, but I would impress upon him the necessity of studying the actual loadings as well as the shape of the load curves.

A study of the curves in Figs. G, H, and J may enable Mr. Dundas to take a more optimistic view of the "on tap" heating load under thermostatic control. Experience indicates that millions of units could be sold each year if rates of the order of 24 units per shilling could be quoted for the day load, and from 30 to 36 units per shilling for the night load, for thermostatically

controlled heating loads on tap 24 hours per day throughout the year. At rates of the order of 16 and 24 units per shilling respectively, the load can be developed, but progress will not be rapid.

Mr. Jenkins expresses the opinion that the smell and stuffy feeling associated with central-heating systems are due to the excess of humidity set up by a high-temperature installation. Several speakers at the E.D.A. Conference, which I addressed on the 24th March, mentioned that they considered that the tubular heaters operated at an excessive temperature, and stated that when switched on, after standing for a day or so, smoke could be observed ascending from the tubes, due to the decomposition of the dust that had settled upon them. These statements confirm the views of several investigators regarding the objections to high temperature surfaces that I reprinted on pages 1056 and 1057 (vol. 69). Regarding the question of humidity, the capacity of air to absorb moisture increases with increasing temperature, as shown in Table A.

per day, are a few of the necessary "luxuries" of modern life. The potential market for the sale of electric heating units is very much larger than Mr. Wells mentions. There are at present some 650 authorized distributors of electrical energy. If only 500 will decide each to obtain 500 electrically heated rooms in their respective areas—500 buildings of one room each, or 250 buildings of 2 rooms each, or 100 buildings of 5 rooms each—the total will be 250 000 rooms. The consumption will probably average 2 000 units per room, and the total is 500 000 000 units per annum. This would be merely the test—and the real development would follow.

BIRMINGHAM.

I am inclined to agree with Mr. Reynolds that there is a very large future for domestic electric heating of the combined form, and I think it is possible that considerable economies can be effected by this method. I refer to the combination of the low-temperature type for

TABLE A.

Grains of Water which Air is Capable of Absorbing to the Point of Maximum Saturation, in Grains per Cubic Foot, for Various Temperatures.

Deg. F.	25	30	35	40	45	50	55	60	65	70
Grains per cub. ft.	1·85	2·19	2·59	3·06	3·61	4·24	4·97	5·02	6·81	7·94

Relative humidity is defined as the ratio of the weight of water vapour in a given space as compared with the weight which the same space is capable of containing when fully saturated at the same temperature. For example, if on a dry frosty day the dry bulb or ordinary air thermometer reads 30° F. and the relative humidity is 56 per cent, the amount of water vapour contained in each cubic foot of air will be 1·08 grains. If the air be now warmed up to 65° F., without the addition of moisture, 6·78 grains would be required to saturate (100 per cent relative humidity), but as there are only 1·08 grains present the *relative* humidity is only 16 per cent, *which is comparable for dryness with the Sahara desert.* Values quoted by various authorities for the weight of water vapour exhaled per hour are the following:—Man at work 0·267 lb., man at rest 0·155 lb., youth 0·088 lb., infant 0·029 lb. Mr. Jenkins mentions that many people insist upon seeing a glowing source of heat. It is merely the association of the idea of comfort with the glowing fire, just as the cow associates the idea of the process of milking with the byre, and the horse associates the idea of a feed with the appearance of his nose-bag.

In reply to Mr. Wells I have tried the intermittent heating method, by means of electric and also gas fires in my own house, and it was the entire failure of the experiment to provide a sense of *real* comfort, as differentiated from *make-believe* comfort, that caused me to change over to continuous heating under thermostatic control. Dry towels and steamless mirrors in a warm bathroom, at every hour of the day and for a few pence maintaining a temperature of 56° F. throughout the house, with the possible exception of the bathroom—which would be at 65° F.—and the use of 1 000-watt fires as boosters in the rooms when they are occupied. The figures given by Mr. Platt for the annual heating of two factories are extraordinarily low, but he does not state the temperature maintained within the buildings, and he does not give the figures for the correlated expenses. In any case, I have not advocated the employment of electricity for heating factories, but I do maintain that there is a vast field on the domestic side where labour is difficult.

Prof. Cramp touches on an interesting and debatable point when he mentions his preference for the visible type of radiant heater. The difficulty we experience is in the practical application of the principle. Invisible radiation is simple to apply and to control and maintains a condition of comfort *throughout* the room, and it is an easy matter to supplement it with a visible type of radiant heater when desired.

Dr. Sims enlarges on the merits of the unit type of thermal-storage heater. While we shall all welcome the addition of this weapon to our electrical armoury, to enable us to wage an even more vigorous offensive during the coming campaign, I feel that it has very marked limitations. I should like to hear further details regarding the weight, the operating temperature, the views of the insurance companies, and the atmospheric condition produced—particularly as regards the characteristic smell invariably associated with high-temperature convection-type heaters. Another point

for consideration is the duplicate wiring systems involved in the larger buildings, and this at the time when the Commissioners are pressing forward the ideal of the two-part tariff with a flat rate for all current metered.

The figures given by Mr. Hooper are interesting and more or less endorse the views regarding thermal storage that I expressed in the paper, although the installation was only designed for a temperature-rise of 25 deg. F. The price of 1d. quoted was, of course, quite unreasonable, and indicated that the supply authority did not desire the load.

I note that Dr. Gifford favours intermittent rather than continuous heating, but I hope that he will see his way to operate the installation continuously next winter, and that he will publish his views regarding comfort and also the costs of operation, after negotiating with the supply authority for a specially low night rate. I feel confident that the results will be to his satisfaction.

I am sorry to see that Mr. Engholm still considers that the cost of heating by electricity is about 17 times the cost of heating by hot water or by steam. If this is actually a fact, then the cost of heating my own dining-room (see Appendix IX, pages 1087 and 1088) would have been somewhere about 7s. for the season, which is rather remarkable, and exceeds the most optimistic statements of the manufacturers of hot-water boilers and radiators. Similarly, the cost of heating the suite of offices detailed in Appendix II would have been £2 10s., which is the price of about 1¼ tons of coke—again a surprising result. Labour and other correlated costs are neglected in these figures, but if they were taken into account the fuel consumption would be reduced to a value approximating to zero and might even be a minus quantity! Up to the time of writing I have had no experience with the unit heaters fitted with electric tubular heaters, and I have no data regarding costs.

Glasgow.

Dr. Parker Smith expresses fears regarding the cost of continuous heating by the ceiling-panel system, but reference to Appendix II should assist in reassuring him. The total cost of nine rooms was £42 4s. 2d., thus giving an average price of approximately £4 15s. per room for the season, and an average cost per room per day of 5¼d. This was obtained with current at 0·675d. per unit, and I consider that there are good prospects of securing even better rates than this in the near future.

I regret that I cannot give Mr. Macleod any assistance in regard to the problem of heating glass-houses, but I think that the operating costs have been very much over-estimated and that investigation will show that there are distinct possibilities, when all the correlated items are taken into account, e.g. equally good results are obtainable with lower temperatures than the gardener demands, when thermostatic control is employed and an even temperature is maintained; the effect of the sun on the glass is much greater than the average engineer allows for (Carrier places it at 150 B.Th.U. per sq. ft. per hour); the efficiency of utilization is much higher with electricity than with coke-fired boilers; and no labour is involved in the distribution of electricity to the various houses, and none in stoking or in regulating the temperature on those days when we get rapid alternations of sunlight and cloud. I am told that this last-mentioned item is a very important one.

Mr. Seddon is to be congratulated on the results that he has achieved in Edinburgh with the tubular form of electric heating; evidently the users are satisfied as I understand the mileage is rapidly increasing, at the rate of 316 kW per mile. This is a strange phenomenon, occurring as it does in Scotland, if we are to credit the views expressed by Mr. Engholm ("electricity is 17 times more costly than hot water"), of Mr. Anderson ("that so much endeavour should have been expended in so poor a cause"), and of Mr. Kilburn Scott ("the idea of using it . . . appears to me to be nonsensical"). My references to the desirability of the interlocking switch on the convector, and to the fact that the maid threw the bedclothes over a glowing electric fire, were intended to indicate that people do the most unexpected things, so that they might even attempt to clean the convector when it was switched on. Only last week it was reported that a lady used an electric hair dryer while she was in her bath—with fatal results. A friend of mine, desiring a hot bath, immersed the electric kettle in the bath after filling the bath with cold water. I was called on to explain why he received a severe shock when he tested the temperature of the water by immersing his elbow in the bath. Mr. Seddon refers to the higher operating temperature of tubular heaters of the chromium-plated type. I stressed this aspect of the subject on page 1076 (vol. 69), and gave the results of a test on various surfaces in Fig. 20.

In reply to Mr. Connor, owing to the very low operating temperature of the thin Dulrae panel no difficulties are experienced by reason of unequal expansion.

Mr. Johnston asks for information concerning the ventilation of rooms equipped with the ceiling-panel system and I would refer him to paragraph 4 in Section (2) of the paper. I consider that all rooms should be provided with means of ventilation for use if and when required. Regarding the effect of a waterlogged ceiling on the ceiling-panel system, we inadvertently made this experiment at the office during a recent week-end. On arriving on Monday morning we found two ceilings, the carpet, and the floor below soaked. The ceiling-panel material was still adhering to the ceiling, the fuses had blown, and there was only a scorch mark half an inch long to indicate where the element wire had burned through. The lighting installation was out of action, the circuit had to be re-wired, and the room had to be re-decorated, so that the cost of renewing the ceiling panel was a minor one.

Mr. Ure appears to complain that the times are moving too fast for him, but surely this is an advantage rather than a handicap, because it means that every six years he can inform his friends that their equipment is out of date, and that he would like to quote them for modernizing their installations.

I agree with Mr. Brassington that a large number of proposals for electric heating are rejected on the score of operating cost, and that was one of my reasons for writing the paper. The discussion at 16 meetings has afforded me an unique opportunity of conferring with electrical engineers all over the country and of discussing

the pros and cons of the subject. With coal at 18s. per ton the electrical heating proposition is somewhat difficult for the larger installations, but even at that price there is a large domestic field, as Mr. Seddon has indicated. I do not agree that the apparatus is dear, for investigation will show that it compares most favourably with the cost of good-class hot-water boilers, pipes, and radiators, and with electricity there is no labour, dirt, or trouble, and no boiler house, fuel store, chimney stack, or ash pit.

While the general public is notoriously conservative, I feel that Prof. Howe has struck an unduly pessimistic note regarding the difficulty of educating it to new methods. I have personal knowledge of one thermostatically controlled tubular installation where the lady of the house invites her friends to tea in order to display her latest triumph. On each occasion the operation of the thermostat is described in detail, and the comfort provided by the installation is eulogistically explained. The invitations are invariably accepted, as I am informed that it is one of the few houses in the district that are *really* warm and comfortable.

I am glad to have Mr. Low's confirmation of the lower temperature found desirable in the panel-heated sections of the hospital to which he refers, and it will be recalled that I have already mentioned that a rise of 5 deg. F. represents an increase of 25 per cent in the fuel bill. I should also like to point out that, during the prevalence of the fogs to which Mr. Low refers, the lighting load (and therefore the casual heat from this source) is at a maximum, so that the thermostatically controlled heating load will be at a minimum. It is also a fact that periods of intense cold do not coincide with dense fogs, because wind is entirely absent, and the radiation from earth to space is restricted by the blanket of fog. The intensely cold weather invariably coincides with the clear, starry nights when the radiation from earth to space is at a maximum. The low-temperature electric panel system has been approved not only by the leading insurance companies, but also by the Board of Trade, and Lloyd's for installation on the C.P.R. boat "The Duchess of Richmond," and is now being considered with a view to use on railway rolling-stock and also on tramcars.

BRISTOL.

I note that Mr. Parker considers the figure of 2 000 units per annum per room to be on the high side, and that he refers to a house where the consumption averaged just over 1 000 units per room. At the same time he mentions a temperature of 55° F. as being adequate for the average home. I think that it will be generally agreed that 63° F. is the minimum temperature for comfort in any occupied room that is warmed by a convection system, and that 65° F. is very generally demanded. The lower figure of 55° F. provides a fair degree of comfort in bedrooms, corridors, and similar rooms, provided that the temperature is boosted up to 63° F. or 65° F. when the dining-room, lounge, etc., are occupied. I am entirely in agreement with Mr. Parker when he expresses regret that other speakers considered it necessary to decry the use of electricity for heating, particularly as their remarks generally indicated that they were not speaking from actual personal experience of thermostatically controlled installations but merely as the results of calculations made on entirely incorrect assumptions.

In reply to Mr. Smith, I feel that heat insulation will play a very much larger part in the design and construction of buildings than it has done hitherto, and here I would sound a note of warning regarding the use of the ordinary cavity wall for this purpose. Tests have shown that the air circulates in the cavity, is cooled by contact with the outer wall and thereby lowers the insulation efficiency. A considerable loss also takes place by reason of radiation from the outer surface of the inner wall to the inner surface of the outer wall. Effective means should be employed to prevent the circulation of the air, e.g. by the use of special bricks. Fig. 7 was included in the paper for the purpose of indicating the unsatisfactory results obtained when the intermittent system of operation was adopted, the current being switched on at 4 a.m. and off at 4 p.m. daily, with the exception of Saturday when it was switched off at 12 noon. The curve from 12 noon Saturday to 4 a.m. Monday shows the rate of cooling and also the effect of the normal rise and fall of the outdoor temperature on the indoor temperature. Fig. 12 is the corresponding curve for the room with continuous heating.

In reply to Mr. Bowman, the temperatures shown in Fig. 4 on page 1057 (vol. 69) were obtained during the evening, in the ordinary way, the windows being closed. I think that Mr. Bowman is unduly pessimistic regarding the unit charge of the bulk supply. Figures have been mentioned to me of the order of 0·18d. and 0·2d. per unit. Time alone can provide the complete answer to his question.

I am sorry that I cannot inform Mr. Bache how long the ripple system of control of the 2- and 3-rate meters has been in operation, but I hope to publish some further information on this subject shortly. In a wood-joist floor, heat insulation such as 2 in. thick cork slab or magnesia powder is fixed over the ceiling panels to prevent loss of heat into the floor above. In a concrete or tile floor, the ratio of thickness of the material above and below the Dulrae is so large that approximately 95 per cent of the heat is emitted in the downward direction. As a matter of fact, the insulation of the floor of the heated room is frequently of more importance than the insulation of the ceiling, because the heat is radiated from the ceiling to the floor and is absorbed by the floor. If there is a substantial emission of the heat from the floor in a downward direction (conducted to the earth or radiated to the concrete slab), the temperature of the floor cannot build up to the desired degree, and complaints of cold may result. (See also my reply to Mr. Gamage containing further information on this point.) In convection-warmed rooms, high ceiling temperatures are encountered over the whole area and the transmission of heat through the ceiling also involves loss in efficiency. Wherever convection is allowed to occur, dusting is inevitable, and for this reason, among others, panels should always be located in the ceiling. Even the dials of my synchronous clocks are showing signs of dusting over the holes through which the spindles pass, due to the heat

generated by the driving motors. When the heating element is pasted to the flat ceiling, convection currents are eliminated and dusting does not occur.

I regret that Mr. Bowden was not more definite regarding the vital point of operating temperature when he commented adversely on his experience of the ceiling-panel system of heating. In certain cases, to reduce installation costs, it is possible that the surface has been reduced and the operating temperature is therefore necessarily high. Experience indicates that such a course is highly undesirable, not only on account of the discomfort produced, but also on account of the increased operating cost. Temperatures should not exceed 110° F. as a maximum in severe weather and in new buildings. Immediately the building has thoroughly dried out and the steady state has been attained, the area of surface should be such that the desired condition of comfort can be maintained in the room with a panel temperature of the order of from 90 to 95° F. I would refer Mr. Bowden to the remarks made by Mr. Low at Glasgow, regarding the hospital which he mentioned. It is also interesting to note that an Italian deputation, after touring Europe, has recommended the hot-water ceiling-panel system of heating for the new 2 500-bed "Benito Mussolini" hospital in Rome. I feel that I must register a protest regarding the repetition by Mr. Bowden and other contributors to the discussion who call for "the education or conversion of the architect." I should like to assure all these gentlemen, from personal knowledge, that the architects and the consumers are fully alive to the benefits of "doing it electrically," and desire to adopt electrical heating wherever possible. Their apparent apathy is the result of years of experience of the sales methods and tariffs adopted by the electrical industry. Let us advertise in a popular manner low rates for the thermostatically controlled continuous heating load, adopt modern methods of salesmanship, and eliminate from our minds the idea of "educating" the architect.

The point raised by Prof. Robertson regarding the use of thicker window glass in order to reduce the heat loss is an interesting one and one that merits further study. The well-known authority Prof. R. C. Carpenter of Cornell University,* quoting from a lengthy translation of "Traité de la Chaleur" (Péclet, 7th edn., p. 75), states . . . "the heat transmitted through glass is independent both of the thickness and the coefficient of conductivity." I would refer Prof. Robertson to one of the books mentioned for the full mathematical investigation that led Péclet to arrive at this conclusion.

When Mr. Gamage criticized Table 4 (page 1054, vol. 69) and referred to the difference in grading between thermal-storage and low-temperature embedded ceiling panels, I think that he overlooked the space required by the storage cylinders and connecting pipes and valves; the loss of heat from the pipes and the cylinders and energy required for the circulating pumps; the chases and trenches and special provision required in the floors to take the panel pipes; the attendance required on pumps, motors, valve glands, feed tanks, relays, thermostats, automatic gear, and electrodes or immersion heaters. It is also a fact that where large quantities of water are contained in a heating installation that is located below sewer-level, the question of flooding and drainage cannot be entirely ignored. I think that the figures given in Appendix X have served the purpose that I intended, which was to draw attention to the fact that a low unit price was not the sole factor and that there were many other correlated items to be taken into account before a correct conclusion could be drawn. As a matter of fact, the figures quoted for both systems are now out of date. The figures given in Appendices V and VI were never intended to be comparable, but were merely intended to indicate the progress that had been made to date and that energy was being sold in large blocks, despite the theoretical disadvantages of electrical heating. (See footnotes to Appendix VI in confirmation of this statement.) Mr. Gamage cannot have it both ways. If, with the thermal-storage system, thermostatic control to the individual rooms is not provided, then there is a very substantial waste of energy. If the rooms are provided with thermostatic control, then the capital cost is substantially increased. The loss of heat from the circulating pipes is again taken exception to, but I have already dealt with this. In domestic supplies, in the pipe-runs actually obtainable in practice, it is usually found that the loss of heat from the pipes equals or exceeds the heat required to heat the water actually drawn from the taps. In other words, in an actual installation, if the actual water used requires a daily expenditure of 500 kWh, then another 500 kWh would be required to make good the heat loss from the circulating pipes, and the total consumption would be 1 000 kWh per day. This is one of the reasons why electrical water-heating is making such rapid progress. Heat energy can be more efficiently distributed throughout a large building by electricity than by hot water. This statement also reveals another reason why electrical heating is economically possible. In one building, investigated only this week, that required 1 000 000 B.Th.U. for heating, the estimate of the heat loss from the domestic hot-water supply pipes of 100 000 B.Th.U. per hour was criticized as being inadequate. It will be agreed that such values are a substantial contribution to the casual heat that the thermostat takes full advantage of. In regard to the heat loss through the back of ceiling panels, it is now standard practice, in wood-joist floors, to employ heat insulation comprising 2 in. thick compressed cork or one of the insulating powders. It may be of interest to note that the insulation of the wood-joist floor of the room marked "Accounts" (already covered by thick linoleum) mentioned in Appendix II, was recently further insulated with $\frac{5}{8}$ in. of "Celotex" board, and a 3-in. layer of insulating powder was spread between the joists. This additional insulation of the floor of the room has resulted in the energy consumption being reduced by 38 per cent for the same temperature-rise. I am sorry that Mr. Gamage does not agree with my view that the inverse-square law is inapplicable to the very extended sources of heat employed in the low-temperature ceiling-panel system. The fact remains that rooms or halls, of ceiling heights of 20 and 30 ft., are satisfactorily warmed by this method, and so I leave Mr. Gamage to suggest the explanation. With regard to the air temperature shown in Fig. 3, the

* "Heating and Ventilating Buildings."

furniture and the observers were not shown in the diagram, as it was not thought necessary to include these details. The air thermometer was located on a desk, and it is probable that this piece of furniture absorbed heat direct from the 300-watt lamp. Other explanations may be that the surface temperatures were taken by means of a Cambridge thermo-couple, and that the air temperature was registered by an ordinary glass-stem thermometer. Anyone who has had experience with commercial thermometers knows how difficult it is to get two thermometers, not specially calibrated, to read exactly the same temperature when hung side by side. I note that Mr. Gamage takes exception to the temperature of 62 or 63° F. It would be interesting to know what experience he has had with this system, and the temperatures he recommends and finds that his clients accept as satisfactory. Again, he indicates that rooms warmed by the low-temperature ceiling-panel system suffer from cold and draughty floors. If this is really the case, how does he explain the fact that the leading architects and the Government departments specify the system repeatedly? He inquires whether I would advocate the continuous heating of churches. In reply, I would say that I have still to find a church that is heated satisfactorily and is entirely free from down-draughts. Almost invariably people wear their overcoats and outdoor clothes during the service, thereby indicating that the outdoor conditions have been merely mitigated, which is very different from creating a condition of "perfect comfort."

In reply to Mr. Moffat, the operating temperature of the low-temperature ceiling panel is of the order of 85° to 100° F., and the life is indefinite, due to the low operating temperature of the element. I do not quite understand the logic of Mr. Moffat's argument, that because the floor temperature is 72° F. the temperature a few inches above the floor is 60° F., and at 100 ft. above floor-level it is 58½° F., in the Liverpool Cathedral (which is heated by floor panels), therefore floor panel-heating is desirable. Fig. 3 shows a more even temperature distribution, with the objectionable warm floor eliminated. Fig. 4 appears to me to indicate the desirability of floor warming to a more marked degree.

In reply to Mr. Hill, so far as I am aware no difficulty is experienced with a multiplicity of ripples on the Paris network, where the triple meter dials are operated by means of a superimposed musical frequency. The company are the only people who are authorized to inject these ripples, and either the sine wave is free from harmonics or, if any are present, their character is such that they do not interfere with the operation of the meters. Chokes are inserted at appropriate points in order to prevent the ripples from travelling beyond the predetermined areas of supply.

LOUGHBOROUGH.

I do not think that any useful purpose will be served by a detailed reply to the opening remarks by Mr. Grogan, as most of the points to which he refers are largely matters of opinion, and several have already been dealt with in my reply to other speakers. His argument, that because radiation becomes more intense at certain temperatures the property should not be employed at lower temperatures, leads to dangerous ground at once. One has only to recall that many of the dangerous poisons are beneficial if employed in small doses, and, in our own profession, while high voltages at 50 cycles are extremely dangerous, low-voltage currents (230–400 volts) are extremely useful for general work. In reply to his inquiry as to how I can justify the claim for radiant heating by low-temperature ceiling panels, I would remind Mr. Grogan that a block of ice can be made to boil a kettle of liquid air, purely by means of the radiant heat emitted by the ice. I would also refer him to the statement of Dr. Margaret Fishenden on page 1057 (vol. 69). In his defence of the small high-temperature source of heat, as exemplified in the electric fire, I think that Mr. Grogan will be interested in the views of Dr. H. M. Vernon, Investigator for the Industrial Research Board:* "In rooms warmed only by a gas fire, however, the inmates are apt to feel scorched on the side of the body exposed to the fire and too cold on the unexposed side." Again, "A person sitting in a room heated by a fire, in addition to receiving positive radiation from the fire and objects warmed by it, is also subject, as a rule, to what may be termed *negative* radiation from the windows, as they are generally colder than the air of the room." I am sorry that Mr. Grogan does not consider that we are justified in reducing the loading of the room, detailed in Table 7, by taking only 25 per cent of the full air losses, but the method cannot be really so reprehensible as Mr. Grogan would have us believe, in view of the fact that it has provided entirely satisfactory results in many buildings of the type mentioned on pages 1048 and 1049 (vol. 69). Again, Mr. Grogan criticizes the consumption shown in Appendix II, and suggests intermittent operation, but the results of the attempts are shown in Fig. 7, while the results of continuous operation are shown in Fig. 12. Regarding the results shown in Appendix IX, I am sorry that I must again disagree with Mr. Grogan, as these are the figures for my own dining-room, and when we adopted the intermittent system that he advocates we found it necessary to breakfast in our overcoats during spells of cold weather. These are results, and should not be confused with calculations or estimates. Again, I am sorry that Mr. Grogan did not produce the estimates, consumption, and thermograph charts for the rooms in his own residence. They would have been so much more convincing than the mass of estimates that he has produced. In regard to the table of costs that Mr. Grogan has prepared, I would refer him to the paragraph on page 1082 (vol. 69) in which I stated that many successful concerns are to-day selling large numbers of cars, the *annual cost* of which, to their respective owners, exceeds the *capital cost* of at least four, and possibly five, cars of the "baby" class. The reply to Mr. Grogan's final question is that many architects refuse to contemplate the types of heating installations that he advocates, and invariably employs the low-temperature ceiling-panel system, for the same reason that a very large number of people are prepared to pay relatively high prices for the necessities and the amenities of life—they consider that the results justify the additional cost, e.g. the extra cost of first-class fares over third-class fares.

* "The Measurement of Radiant Heat in Relation to Human Comfort," *Journal of Industrial Hygiene*, 1932, vol. 14, p. 110.

In reply to Mr. Webb's inquiry as to where the thermostat should be placed, I can only give general suggestions. The fundamental consideration is that it should be located where it is affected by the average conditions prevailing in the room—*not* in the draught from the door, *not* in the immediate vicinity of the heater, and *not* in a cupboard under the stairs and alongside the meters, as has been suggested to me on more than one occasion. Behind the door, and at a height of 5 ft., usually gives good results, but in some rooms it is desirable to fix it on the window wall, in order to ensure that the temperature is adequately maintained during spells of cold weather. As the thermostat will handle from 10 to 15 amperes (a.c.) without the interposition of a relay, the normal blocks of load are from 2 to 3 kW per thermostat. The corresponding cubes are difficult to state as they vary so greatly, but at 0·5 watt per cubic foot the space is obviously from 4 000 to 6 000 ft.

I should like to give a definite reply to the question put to me by Mr. Furse, but I do not consider that the time is yet ripe for such close comparisons, and one cannot ignore the correlated costs to which I have repeatedly referred in the paper. I think that the better course is to prepare a statement of costs for each individual installation. As an example, a difference of 1d. per day per room in a small house would probably be worth while paying. On the other hand, in a building of 500 rooms the additional cost per year becomes a substantial item and may not be justified. I would also refer Mr. Furse to my reply to Mr. Carr (Newcastle), in which I indicated the danger of the figures being misapplied. Thermostats incorporating a mercury tube are now available for use on d.c. circuits. As stated on page 1067 (vol. 69), the Satchwell thermostat will handle 0·1 ampere on d.c. circuits, and can be utilized to operate relays of the mercury tube or the contactor type, but this method usually involves an increase in the cost of wiring.

The positive statement by Mr. Driver regarding the great success of the electric heating of eight classrooms at Loughborough College is very welcome after the mass of adverse criticism expressed by so many members. It is also particularly interesting to note that, as a result of this test, the hall of residence for 90 students is to be similarly equipped. The low-temperature ceiling-panel system is essentially a continuous heating system, and has been especially developed for thermostatic control with a view to improving the load factor of the supply authority, and thereby qualifying for low-priced tariffs. Rapid heating inevitably involves heavy loading, large mains, peak loads, and bad load factors. Mr. Driver refers to " gradual heating," whereas I regard the problem as one of preventing excessive cooling, and particularly one of maintaining all rooms in a house above the dew point. In reply to Mr. Driver's criticism of " stuffing up the cracks," I can only refer him, once again, to the notes on pages 1064 and 1065 regarding this detail—particularly to the words printed in italics, "*for purposes of calculation only*." I do not know whether the suggestion to fix tubular heaters at picture-rail height is intended to be taken seriously. A large percentage of the heat emitted by the tubular heater is undoubtedly transmitted by convection, and it therefore follows that they should be located as near the floor as possible, except when they are employed for the purpose of preventing down-draughts from roof-lights (see also Fig. 4 for temperatures). The convection currents will inevitably deposit dust on the frieze.

I am in agreement with Mr. Jockel regarding the question of tariffs, and I am of the opinion that the type illustrated in Fig. 21 is worth very close study. The results obtained by the City of London Co., working along these lines, are stated to be very encouraging. The figure of 1·40 watts per cubic foot is unusually high, average values being of the order of 0·5 or 0·6 watt per cubic foot for the average rooms, whereas values of 0·2 or 0·3 are frequently obtained for the larger buildings. As I mentioned in my reply to a previous speaker, I hope to publish further information relating to the ripple-controlled 2- and 3-rate meters at a later date.

The remarks of Mr. Gill again come as a welcome counterblast to the criticism based on estimates and not on actual experience. Is it too much to hope that the sceptics will abandon their slide-rules and calculations, and spend their time and energy in installing electric heating and thermostatic control equipment, and in publishing their expressions of satisfaction?

Has Mr. Duncan never "rushed a hill" when driving a car? The extra burst of speed stores energy and the car breasts the hill with little or no effort. The walls of a 20-ft. × 16-ft. room have a total length of 72 ft., and if the height is 9 ft. 6 in. the gross superficial area is 684 sq. ft. Deduct the odd 84 sq. ft. for windows and doors, and the net area is 600 sq. ft. Assuming the walls to be 9 in. thick, the volume of brickwork is 450 cub. ft., which at 120 lb. per cub. ft. gives a total weight of 54 000 lb. Assume the specific heat to be 0·2 and we find that every degree Fahrenheit represents 10 800 B.Th.U. or 3·1 kWh. Thermal storage of this type is extremely useful to rush the cold spells, and indicates the "flywheel effect" available in the average building to smooth out the load curve. I have experienced difficulty in following Mr. Duncan's argument when he states that my theory does not apply in one single instance to the guaranteed figures for the running costs of tubular and other systems to which he has access. It is unfortunate that he does not publish facts and figures to support his statement. Again I fail to follow his argument when he refers to the impossibility of obtaining uniform temperatures with a low-temperature panel system. Conversely, I think that it must be self-evident that where a uniform temperature is essential, extensive areas of walls, ceilings, and floors at temperatures only slightly in excess of the desired temperatures are clearly indicated. Proof of this statement will be found in Figs. 3 and 4, and also in the remarks by Mr. Moffat at the Bristol meeting.

General Reply.

The undermentioned points appear to call for a brief review.

Economic Practicability of Electric Heating.—While I do not consider that factories, prisons, poor-law institutions, municipal housing estates, and buildings that fall into similar categories will be electrically heated in the near

TABLE B.—*Maximum, Minimum, and Mean Temperatures* (° F.) *for Various Stations throughout the British Isles.*

Compiled from readings taken during the years 1881–1915. (Selected from "The Book of Normals of Meteorological Elements for the British Isles for periods ending 1915," H.M. Stationery Office, 1919, 2s. net.)

Month	Aberdeen			Bath			Belfast			Birmingham		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
January	42·3	33·2	37·8	44·7	33·8	39·3	45·1	34·3	39·7	42·0	33·6	37·8
February	43·4	33·1	38·3	46·6	33·9	40·3	46·6	34·5	40·6	43·7	34·1	38·9
March	46·0	34·3	40·3	49·8	34·8	42·3	48·8	35·1	42·0	47·1	35·0	41·1
April	50·2	37·5	43·9	55·2	38·7	47·0	53·4	39·0	46·2	53·2	38·4	45·8
May	54·9	41·7	48·3	61·8	44·1	53·0	59·0	43·4	51·2	59·8	43·8	51·8
June	60·2	47·0	53·6	66·8	49·8	58·3	64·1	49·0	56·6	65·5	49·4	57·5
July	63·1	50·2	56·7	69·8	53·2	61·5	66·3	51·5	58·9	68·4	52·7	60·6
August	62·7	49·8	56·3	69·2	52·2	60·7	65·4	51·5	58·5	67·0	52·0	59·5
September	59·5	46·6	53·1	65·4	48·0	56·7	61·8	48·0	54·9	62·5	48·8	55·7
October	53·0	41·6	47·3	57·5	42·3	49·9	55·5	42·1	48·8	54·0	43·2	48·6
November	46·9	37·2	42·1	50·4	37·4	43·9	49·6	36·8	43·2	47·6	38·4	43·0
December	42·9	34·0	38·5	46·5	35·1	40·8	46·0	35·1	40·6	43·2	34·9	39·1
Year	52·1	40·5	46·3	57·0	41·9	49·5	55·1	41·7	48·4	54·5	42·0	48·3
October to April ..	46·4	35·8	41·1	50·1	36·5	43·3	49·3	36·7	43·0	47·2	36·8	42·0

	Bournemouth			Brighton			Cardiff			Cork (Ballinacurra)		
January	44·7	34·8	39·8	44·1	35·8	40·0	43·6	34·1	38·9	47·7	37·0	42·4
February	46·1	35·2	40·7	45·2	36·3	40·8	45·1	34·9	40·0	48·3	37·4	42·9
March	49·1	36·1	42·8	48·1	37·4	42·8	48·3	35·6	42·0	50·3	37·5	43·9
April	55·1	39·3	47·2	53·9	41·2	47·6	53·6	39·5	46·6	54·5	40·5	47·5
May	61·5	44·5	53·0	60·7	46·6	53·7	60·0	44·6	52·3	59·4	44·9	52·2
June	66·6	49·9	58·3	65·7	52·0	58·9	65·4	50·2	57·8	64·8	49·5	57·2
July	69·7	53·3	61·5	68·9	55·4	62·2	67·7	53·2	60·5	67·3	52·2	59·8
August	69·3	53·1	61·2	68·8	55·5	62·2	67·2	52·8	60·0	66·6	52·2	59·4
September	65·4	49·4	57·4	65·5	52·2	58·9	63·1	49·1	56·1	63·3	49·6	56·5
October	57·4	44·4	50·9	57·8	46·5	52·2	55·7	43·9	49·8	56·7	44·0	50·4
November	50·7	39·4	45·1	50·7	41·5	46·1	49·1	38·3	43·7	51·5	39·5	45·5
December	46·3	36·9	41·6	46·2	37·8	42·0	45·4	36·3	40·9	48·6	37·5	43·1
Year	56·9	43·0	50·0	56·3	44·9	50·6	55·4	42·7	49·1	56·6	43·5	50·1
October to April ..	49·9	38·0	44·0	49·4	39·5	44·5	48·7	37·5	43·1	51·1	39·1	45·0

	Dublin (Glasnevin)			Dumfries			Dundee			Durham		
January	46·0	35·2	40·6	42·8	33·1	38·0	41·3	32·8	37·1	42·0	32·2	37·1
February	47·2	35·2	41·2	44·4	33·1	38·8	42·5	32·5	37·5	43·5	32·3	37·9
March	49·3	35·5	42·4	47·4	34·1	40·8	45·8	33·7	39·8	46·8	33·3	40·1
April	53·5	38·2	45·9	53·7	37·1	45·4	51·4	36·7	44·1	52·0	36·1	44·1
May	58·6	42·5	50·6	59·6	42·1	50·9	57·2	41·6	49·4	57·3	40·8	49·1
June	64·3	48·1	56·2	65·7	48·0	56·9	63·6	47·2	55·4	64·0	46·6	55·3
July	66·9	51·4	59·2	67·0	50·9	59·0	66·3	50·5	58·4	67·3	50·2	58·8
August	66·2	50·7	58·5	65·8	50·1	58·0	64·8	49·7	57·3	66·0	49·7	57·9
September	62·6	47·0	54·8	62·4	46·1	54·3	60·6	46·4	53·5	61·6	46·3	54·0
October	55·8	41·8	48·8	54·6	40·9	47·8	52·5	40·9	46·7	53·7	41·0	47·4
November	50·4	38·3	44·4	47·7	36·8	42·3	46·1	36·5	41·3	47·3	36·7	42·0
December	46·8	35·7	41·3	43·5	34·0	38·8	42·0	33·2	37·6	42·8	33·3	38·1
Year	55·6	41·6	48·6	54·6	40·5	47·6	52·8	40·1	46·5	53·7	39·9	46·8
October to April ..	49·8	37·1	43·5	48·0	35·5	41·7	45·9	35·1	40·5	46·8	34·9	40·8

TABLE B—*continued.*

Month	Edinburgh (Leith)			Falmouth			Glasgow			Hull		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
January	44·0	34·2	39·1	46·9	39·9	43·4	42·4	34·8	38·6	42·6	32·7	37·7
February	45·2	33·8	39·5	47·1	39·6	43·4	43·2	35·0	39·1	44·7	33·1	38·9
March	47·7	34·9	41·3	48·7	39·8	44·3	45·5	35·7	40·6	48·1	33·9	41·0
April	52·6	38·1	45·4	52·6	42·9	47·8	51·2	38·8	45·0	53·2	36·9	45·1
May	57·3	42·8	50·1	57·7	47 0	52·4	57·2	43·4	50·3	59·2	42·0	50·6
June	62·9	48·4	55·7	62·8	52·0	57·4	62·9	48·6	55·8	65·4	47·6	56·5
July	65·8	51·4	58·6	65·8	55·1	60·5	64·4	51·5	58·0	68·8	51·4	60·1
August	65·4	51·2	58·3	65·4	55·1	60·3	63·1	51·0	57·1	68·1	50·7	59·4
September	61·8	47·6	54·7	62·1	52·7	57·4	59·2	47·8	53·5	63·5	47·2	55·4
October	54·8	42·1	48·5	56·3	47·7	52·0	52·3	42·5	47·4	55·5	41·8	48·7
November	48·5	38·0	43·3	51·6	43·9	47·8	46·7	38·5	42·6	48·5	37·2	42·9
December	44·8	35·0	39·9	48·8	41·6	45·2	43·3	35·7	39·5	43·6	33·8	38·7
Year	54·2	41·7	47·9	55·5	46·6	51·0	52·6	42·0	47·3	55·1	40·7	47·9
October to April ..	48·2	36·5	42·3	50·2	42·2	46·2	46·3	37·2	41·7	48·0	35·6	41·8

	London (St. James's Park)			Manchester (Whitworth Park)			Oxford			Sheffield		
January	44·2	34·9	39·6	43·3	34·8	39·1	43·3	33·5	38·4	42·7	34·2	38·5
February	45·8	35·5	40·7	45·0	35·1	40·1	45·4	34·0	39·7	44·0	34·6	39·3
March	49·5	36·6	43·1	48·1	36·4	42·3	49·2	34·9	42·1	47·0	35·4	41·2
April	55·6	40·7	48·2	54·0	39·5	46·8	55·3	38·6	47·0	52·4	38·7	45·6
May	62·0	46·2	54·1	60·1	45·1	52·6	61·4	44·2	52·8	58·5	43·5	51·0
June	67·4	51·9	59·7	66·0	50·7	58·4	67·0	49·9	58·5	64·6	49·1	56·9
July	71·0	55·3	63·2	68·0	53·6	60·8	70·2	53·5	61·9	67·3	52·7	60·0
August	70·0	54·9	62·5	67·1	52·7	59·9	69·1	52·6	60·9	66·5	52·2	59·4
September	65·4	51·0	58·2	63·4	49·3	56·4	64·8	48·4	56·6	62·3	48·9	55·6
October	57·1	45·2	51·2	55·5	44·0	49·8	56·2	42·5	49·4	54·3	43·5	48·9
November	50·3	39·7	45·0	48·5	38·7	43·6	49·1	37·9	43·5	48·1	39·2	43·7
December	45·9	36·7	41·3	44·5	36·2	40·4	44·6	35·1	39·9	44·0	35·5	39·8
Year	57·0	44·0	50·5	55·3	43·0	49·2	56·3	42·1	49·2	54·3	42·3	48·3
October to April ..	49·7	38·4	44·0	48·4	37·8	43·1	49·0	36·6	42·8	47·5	37·3	42·4

future, I feel even more definitely that there is a vast and ever-increasing scope for the sale of electrical energy for heating purposes. The majority of the adverse criticism has been based on calculations and on estimates built on false assumptions. Men who have had experience of modern installations controlled by thermostats are favourably disposed to the proposition.

For the "direct" type of electric heating the maximum flat rate is of the order of 24 units per shilling (0·5d. per unit), but the rate that will popularize the system is one that will differentiate between day and night, or "off peak," use. Such a rate might be 16 units per shilling for day use (0·75d. per unit) and 48 units per shilling for night and week-end use (0·25d. per unit). Assuming that during a week's run of 168 hours the thermostat is closed for 66 per cent of the time (112 hours), the allocation may be taken as two-thirds of the consumption or 67 hours at the $\frac{1}{4}$d. rate, and the balance of 45 hours at the $\frac{3}{4}$d. rate, thereby giving an average of 0·45d. per unit or 26·7 units per shilling.

For the thermal-storage system to compete with the oil-fired hot-water installation (in which the rooms and also the boilers are under thermostatic control), the oil flame being automatically started and stopped as required to maintain the boiler temperature, the maximum rate which is at all attractive is of the order of 40 units per shilling (0·3d. per unit), but the actual economic rate appears to be as low as 72 units per shilling (0·167d. per unit).

Current Consumption in Various Districts.—In the north it was suggested that my estimates for current consumption were based on the London area, where the climate is milder. To facilitate adjustments for the various districts, I have prepared Table B, showing the average maximum, minimum, and mean temperatures throughout the year, and Table C, showing the variation from the normal or "standard" consumptions.

As an example, if the "standard" consumption, calculated from Table 12, is found to be 10 000 units per annum for a mean temperature of 43° F. and 30 deg. F. rise of temperature, the consumption in Falmouth would be 8 380 units and in Dundee 11 120 units.

Main versus Room Thermostats.—Detailed study of the subject clearly indicates that the great difficulty experienced in the majority of installations is to find the "index room" in which to locate the main thermostat, where only one thermostat is to be installed. Almost every room in a building is subjected, more or less frequently, to some special disturbing factor, and the temperature in the remaining sections of the building will be either too high or too low.

Continuous versus Intermittent Heating.—Probably the main attack on the paper was concentrated on my support of the continuous system of heating, under thermostatic control, as differentiated from the intermittent method of operating the installation. Supply engineers have the matter in their own hands. A flat rate will induce the heavily loaded intermittent installation to become popular, and the peak load will coincide with the breakfast cooking load. Two- or three-rate meters, giving a specially low night and week-end tariff, will encourage the continuous load, and very large blocks of energy will be sold during the slack period. With the experience of both methods—both comfort and cost—I am still convinced that the continuous method is the essential one for real comfort. One cannot be really comfortable in a room in which the furniture, walls, floor, and ceiling are cold, and one is merely warmed by a blanket of air or by a concentrated and highly directional beam of radiant heat.

Margins in Thermal-Storage Installations.—It is interesting to note that practically the whole of the criticism of the margins that I have suggested to cover pipe and cylinder losses, came not from the experienced hot-water engineers who daily design, install, test, and guarantee their installations, but from electrical engineers who were relying on calculations. The practical difficulty experienced in utilizing the pipe losses to assist in heating the building is the fact that pipes must be run where they can be accommodated, and not in the most efficient places. Pipes are only a service, and the building is constructed for purposes other than to form pipe chase. To maintain a corridor at a temperature of 2 deg. F. in excess of the minimum, adds 10 per cent to the cost of energy.

Thermal-Storage versus Direct Heating Installations.—Further consideration has led me to the conclusion that the thermal-storage system will probably lead the field for the larger installations, and that the direct method will be employed for the smaller work. An important feature of the panel-type thermal-storage system that has been overlooked by all speakers is the fact that heat

TABLE C.

Variation of the Mean temperature at Various Stations throughout the British Isles from the Standard of 43° F. adopted as the Basis of Table 12 (page 1078, vol. 69).

Mean temperature for seven winter months	Station	Variation from 43° F.	Mean temperature-rise required to maintain 63° F.	Percentage of 30° F. rise required to maintain 63° F.	Equivalent hours' use of maximum demand (theoretical)	Percentage of "standard" consumption.
°F.		deg. F.	deg. F.	per cent		
46·2	Falmouth	+ 3·2	16·8	56·0	2 855	83·8
45·0	Cork	+ 2·0	18·0	60·1	3 060	90·0
44·5	Brighton	+ 1·5	18·5	61·7	3 150	92·6
44·0	Bournemouth	+ 1·0	19·0	63·3	3 220	94·8
44·0	London	+ 1·0	19·0	63·3	3 220	94·8
43·5	Dublin	+ 0·5	19·5	65·2	3 320	97·8
43·3	Bath	+ 0·3	19·7	65·8	3 355	98·8
43·1	Cardiff	+ 0·1	19·9	66·3	3 380	99·5
43·1	Manchester	+ 0·1	19·9	66·3	3 380	99·5
43·0	Belfast	—	20·0	66·6	3 400	100
42·8	Oxford	− 0·2	20·2	67·5	3 440	101
42·4	Sheffield	− 0·6	20·6	68·8	3 510	103
42·3	Edinburgh	− 0·7	20·7	69·0	3 520	104
42·0	Birmingham	− 1·0	21·0	70·1	3 580	105
41·8	Hull	− 1·2	21·2	70·8	3 610	106
41·7	Dumfries	− 1·3	21·3	71·0	3 620	107
41·7	Glasgow	− 1·3	21·3	71·0	3 620	107
41·1	Aberdeen	− 1·9	21·9	73·0	3 720	109
40·8	Durham	− 2·2	22·2	74·0	3 770	111
40·5	Dundee	− 2·5	22·5	75·0	3 820	112

can be made available at a relatively early stage in the completion of the building for the purpose of drying-out the structure, thereby reducing the time required for construction. This is due to the fact that the pipes are cast with the floors, and that it is not necessary to wait for the completion of any chimney-stack. Assistance of this type in reducing the constructional time for a large building, erected on a valuable site, may be a vital factor in the success of the enterprise.

Coal Conservation.—An interesting side-light on the argument of coal conservation was recently reported when a deputation of prominent men from South Wales waited on Mr. Stanley Baldwin and pressed him to endeavour to persuade the Government to order coal to be used in the Navy in lieu of oil, owing to the intense distress in the coal-mining districts.

Electrode versus Immersion-Heater Boilers.—So long as the multiple earthing of the neutral remains contrary to the Commissioners' Regulations, and so long as supply engineers insist on the installation of 1 : 1 ratio transformers in order to separate their distribution systems from the boiler electrodes, the extra-high-tension type of electrode boiler will make little serious headway. It suffers from the fact that the conductivity of the electrolyte varies both with the concentration or strength and also with the temperature, and this involves complicated automatic regulating equipment. A slight variation of conductivity involves a substantial variation in the load at the high voltages employed. On the other hand, immersion-heater units are manufactured in large quantities, their weak points have been eliminated, and the immersion-heater type of boiler can now be regarded as a very reliable piece of apparatus. The grouping of the units, which are frequently of the 3-kW rating, is rapidly increasing, for whereas, until quite recently, banks of 10 or 25 kW were regarded as standard, in the latest installations the units are banked in groups of 50, 100, and even 150 kW, balanced protective gear being employed for the protection of the individual elements in lieu of fuses or small circuit breakers.

Variation of Temperature of the Tank Water.—A point that requires careful consideration is the apparent loss in storage capacity of the tanks, due to the variation in temperature through the vertical section of the tanks. Circulating pumps have been suggested for the purpose of thorough mixing of the water, so that the temperature is approximately uniform throughout the tanks.

Use of Magnetic Valves.—Marked developments have occurred in connection with the design and manufacture of the solenoid valve illustrated in Fig. 10 of the paper. In a special triple form it is now extensively employed as the modulating valve for automatically maintaining the temperature of the circulation water, by adding, as required, small quantities of hot water from the storage cylinders of the thermal-storage system. It is also found extremely useful in installations where a mixed panel and radiator system is employed. In this case, the boiler runs at the temperature required by the radiators—usually between 180° and 140° F.—and the modulating valve simultaneously maintains the panel circuit at any desired temperature between 120° F. and 90° F. Although the $\frac{1}{2}$-in. valve is only rated at 12 watts, the $\frac{3}{4}$-in. at 15 watts, and the 1-in. at 30 watts, the load is a useful one for the supply authority, where the valves are fitted to room radiators and panels, because the load continues for a substantial part of each 24-hour day, throughout the heating season. In one case that I investigated, the annual consumption for the valve solenoids exceeded the lighting consumption of the building.

Thermostats.—A thermostat is now available for use on a.c. or d.c. circuits in which a mercury switch is combined with a bellows designed to expand and contract with small variations of temperature. The expansion and contraction of the bellows cause the mercury switch to rock and thereby to switch the current on and off and so to maintain the desired temperature. An ingenious type of silent relay takes the form of a "⌶"-shaped glass tube, the horizontal portion of which contains mercury. Contact wires are fused into the opposite ends of the horizontal portion of the ⌶, just clear of the mercury. The vertical leg contains a solenoid core and is surrounded with a magnet coil. When current flows in the coil the core is held clear of the mercury, but when the current is switched off the core falls into the mercury, and by mechanical displacement the level of the mercury rises, thereby electrically connecting the two contact wires that are fused into the glass.

The Heat Insulation of Buildings.—Much more attention is now being paid by architects to this extremely important aspect of building construction, and it is only a logical step to regard the problem of maintaining comfort during the winter months as one of preventing excessive cooling, rather than as one of heating the building. Two small houses were erected at the Building Research Station at Watford, one being of standard 9-in. brick construction and the other of brick and concrete lined with insulating material. The two houses were under thermostatic control, and every precaution was taken to ensure that the conditions would be identical for both houses during the test. The consumption for the brick house was 5 397 units, and for the insulated house 3 342 units, so that the heat insulation effected a saving of 38 per cent. In the new St. Swithun's School, recently erected at Winchester, to the designs of Messrs. Mitchell and Bridgwater, chartered architects, of Hanover Square, special attention was paid to the problem of heat insulation of the floors, walls, and roof, and thermostatic control was utilized. Although the new school has approximately twice the cubic contents of the old school and is in a very exposed position, as compared with a sheltered one, I am informed that the records of the first season (while the building is still being dried out) show that if the heating installation is run for nine months in the year the cost will still barely equal that of the fuel required to heat the old building.

Developments of the Warm-Ceiling System.—The low-temperature ceiling heating system, described on page 1049 (vol. 69), has now been very considerably modified. The latest form consists of a thin card or stiff canvas reinforced paper, in which the element is incorporated. The total thickness of the material is 1 mm, standard widths are 20 and 40 in., and it is available in continuous rolls that can be cut at intervals

of 24 in., so that any desired length may be obtained from the stock rolls. It is pasted to the ceiling in the same way as a substantial lining paper, and may be regarded as non-ignitable when fixed. The maximum surface temperature of the new form is approximately 100° F., and the normal loading is 23 watts per square foot or 75 watts per foot run.

Acknowledgments.—Several speakers have credited me personally with the invention of the low-temperature electric ceiling panel-heating system. In the development work, which has extended over a period of 10 years, I have merely contributed my quota in association with my colleagues, Messrs. J. L. Musgrave, R. G. Crittall, L. J. Fowler, B.A.(Cantab.), and Fernand Billerey.

Conclusion.—The work involved in writing the paper and in replying to the discussion has been most generously repaid by the widespread interest that the paper has aroused in the subject of electrical heating. Evidently it was a subject that required examination, and it will be generally agreed that it has been very thoroughly examined. My sincere thanks are due to all concerned. There are now some 3 000 electrical heating installations other than electric fires in the British Isles, and this total is increasing daily.

DISCUSSION ON "BUSHING INSULATORS FOR OUTDOOR TRANSFORMERS."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH JANUARY, 1932.

Mr. E. T. Norris: The paper may conveniently be divided into two parts, the latter part dealing with practical points in bushing-insulator design and manufacture. It is evident from this part of the paper that the present design and construction of high-voltage bushings is the result of operating experience rather than development based on fundamental principles. The first part of the paper deals with these fundamental principles, and attempts to derive from them the desirable characteristics of a bushing in regard to the transformer itself, the transmission line, and operating conditions. The author rightly describes the characteristics under impulse or surge conditions as being fundamental to the design of a bushing. Knowledge of surge conditions is rapidly developing, and during the last few years many of the early theories and deductions have been completely changed. The conclusion, for example, that the size of a transformer bushing should depend upon whether or not the transformer insulation is graded, is based entirely upon consideration of 50-cycle insulation stresses. The essential principle of graded-insulation transformers is that advantage should be taken of the fact that the neutral point is solidly and permanently earthed, to reduce the insulation to earth at the neutral end of the winding. The principle does not suggest that the line end of the winding should be any less well insulated than in ordinary transformers. Surges and travelling waves entering a transformer from the line impose just as severe a stress on the line end of the winding when the insulation is graded as when it is not. It is essential, therefore, that the insulation at the line end of the winding (this includes the bushing insulation) should not be reduced in graded-insulation transformers. In the first part of the paper the author refers frequently to co-ordination of line, station, and apparatus insulation, the principle being to grade the insulation of the various parts of a transmission system so that when breakdown is necessary to relieve the stress on the system, it occurs at a predetermined point where it can do little damage and will cause a minimum of inconvenience. Such correlation is possible where similar characteristics, e.g. the spark-over voltage of insulators and bushings, are being considered. The nature of the breakdown of such solid insulation as that of a transformer winding or a bushing is so fundamentally different from that of spark-over in air that a comparison can only be made if other and more complicated factors are considered. A bushing or line insulator flashes over when the surge voltage exceeds a certain value, but it will withstand without harm any number of surges of the same wave-shape whose voltage is below that value. A transformer winding or bushing consists largely of solid insulation. It is an important characteristic of such insulation that the damage done by surges is cumulative and progressive. Whilst, therefore, a single surge of sufficient magnitude would break down a given insulation, a number of surges of much smaller magnitude would also break it down. The damage done to an unprotected transformer or bushing by surges is so cumulative that its life will depend entirely upon the number and severity of the surges inflicted upon it. Owing to the erratic distribution of thunderstorms and lightning strokes, this life is governed largely by chance and coincidence. Any attempt, therefore, to co-ordinate line and transformer insulation on the basis just described must include not only the wave-shape of the surge and its maximum amplitude but also the number of surges and the desired life of the transformer or bushing. The author refers to the effect of reflection on a transformer bushing at the end of a transmission line. It is theoretically true that when a surge arrives at the end of a line it will be reflected and its potential may be raised to twice the original value, provided that the wave-front of the surge is rectangular. In practice, even with a rectangular wave-front, this reflected value is only possible during the time taken for the reflected wave to travel the 400 or 500 ft. from the bushing to the first line insulator, a matter of approximately $\frac{1}{2}$ microsecond. This time is too short for the increased surge potential to have any dangerous

* Paper by Mr. W. J. JOHN (see vol. 70, page 297).

effect. Moreover, the wave-front of surges is always sloping, never rectangular. The reflected wave will similarly be sloping, and will be superimposed on the original wave, giving a gradual increase in surge potential which will cause the line-insulator bushing immediately preceding the transformer to flash over and relieve the situation. In other words, the line insulator immediately preceding the transformer gives a very definite protection to the transformer bushing against the increased stresses due to reflection.

Mr. P. G. Ashley: I am disappointed that the author gives so little information regarding the condenser-type bushing. This was first developed by the Westinghouse Co. in March, 1910, since when thousands of condenser bushings manufactured in this country, in Europe generally, and in the U.S.A. have given excellent service. In view of this the statement on page 323 that many users have had trouble with bushings of the condenser type, whilst trouble with the oil-filled type is rare, is unfortunate, as I think it is contrary to engineering experience. Another statement on the same page to which I take exception, chiefly because it requires qualification, is that the condenser bushing is more expensive than the oil-filled type. My experience is that up to 100 kV the prices of the two types are comparable, and that over 100 kV the oil-filled bushing is the cheaper. Other features, however, such as the extra cost involved by switch top-plates, current transformers, etc., due to the larger size of the oil-filled bushing compared with the condenser bushing of the same rating, must be considered when making a comparison between the two types. It is true that recent developments in connection with the use of bushing-type current transformers have enabled the size of the latter to be reduced when used on oil-filled bushings, but, so far as I know, for the same rating the condenser bushing can still be made smaller than the oil-filled type. The principles inherent in the design of the condenser bushing allow the axial gradient at the air and oil ends of the bushing to be controlled, and this must result in smaller dimensions for the same performance. The author states (vol. 70, p. 323) that in his opinion condenser bushings can be obtained which will give no more trouble than any other type. I think that this statement is not a matter of opinion but an actual fact. Even years ago when the technique of bushing manufacture was certainly not at the high state to which it has attained within recent years, the condenser bushing could easily hold its own, and this is more than ever true at the present time. The safety of the oil-filled bushing depends upon the oil remaining in the porcelain top and bottom shells. A small crack in the porcelain or the starting of one of the oil joints will allow the oil gradually to leak away. This is bound to be followed by breakdown. On the other hand, even if the porcelain rain-sheds of a compound-filled condenser bushing were actually broken away, unless weather conditions happened to be very bad the bushing would still operate satisfactorily and thus allow time for alternative supply arrangements to be made. Although the author cites deterioration of the varnish paper as a condemnation of the condenser bushing, in another column he mentions that oil-filled bushings are fitted at the top of the reservoir with a tube open to the atmosphere. Oil is known to deteriorate rapidly on the addition of moisture, and though the tube is turned down to prevent rain from driving into it, moisture-laden air can readily pass into and out of the container. The illustration (Fig. 40) of a 220 000-volt oil circuit-breaker bushing made of porcelain is of particular interest; in this connection I should like to point out that one manufacturer in this country has for some time past been manufacturing complete condenser bushings 16 ft. long, and has also made 500 000-volt condenser bushings up to 24 in. diameter. It is stated that bushings for switchgear have to withstand mechanical stresses due to the shocks of making and breaking contact. One development, however, embodies an arrangement whereby the closing shock is taken on the arc shield enveloping the lower end of the bushing, and it is in fact possible to operate the circuit breaker with the actual condenser bushing removed. The current-carrying capacity of copper rods given in Table 20 does not hold for all designs. I should be glad if the author would state the conditions for which these figures hold good, and the circumstances under which the test reported in Table 22 was carried out. At the same service voltage an air-core porcelain bushing with a 1-in. conductor will carry quite a different current from that which might be carried by an oil-filled bushing or a porcelain-shrouded condenser bushing. On page 314 there is a rather confusing statement to the effect that the minimum commercial thickness of a wall of paxolin is about $\frac{1}{8}$ in. It may be pointed out here that "paxolin" is a proprietary name, and that it would have been better had the author used the term "synthetic resin varnish-treated paper," which has been standardized for this class of material. I assume here that he has in mind the use of a varnish-treated paper tube which will be slipped over the copper conductor by the manufacturer of the composite bushing. In this case it would probably be difficult to make a satisfactory job with a tube of less than $\frac{1}{8}$-in. wall thickness. The practice of pushing an insulating device on to a copper rod is not to be recommended, as it is extremely difficult to ensure that no air space is present between the copper and the internal bore of the tube. In a case of this kind it is much better to have the insulation wound directly on to the copper rod. The radial thickness may then be given any suitable value demanded by the design.

Mr. W. Fennell: With regard to the subject of joints between the bushings and the transformer casing, we are greatly troubled by oil leaks on outdoor transformers having conservators. I have not seen a pressure joint between porcelain and metal which could be regarded as satisfactory. To my mind the proper way to connect the insulator to the tank is to cement a metal ring to the insulator and to use the metal ring for the bolted joint. There is no need to make a new cemented joint each time a bushing is replaced. Instead of keeping the spare bushing separate from the ring, keep it cemented to the ring. The change may be effected in a few minutes, as one has only to make an ordinary metal-to-metal joint. I have specified this construction on several occasions, after somewhat serious trouble through leaving the matter open for the transformer manufacturer to decide. In

my opinion there is much unnecessary elaboration in regard to bushing insulators. For example, take the kinds of insulators to be used according to whether the star point is earthed or insulated. The paper shows that the specifications of the two do not differ greatly, and as regards appearance one would not know them apart. I do not think it is necessary or advisable to design a transformer bushing except on the assumption that the circuit is insulated. Transformers for voltages up to 33 000 volts are used in all sorts of situations. A transformer should be so constructed that it can be used anywhere, and therefore the highest possible surge voltage is the important consideration, not the question whether the star point is earthed or insulated. A great source of oil leakage with transformer bushings is the conducting rod in the middle. I do not think we have more than two or three transformers with conservators that do not leak at that point. The oil spreads down the bushing outside, collecting flies, dust, and filth. We therefore have to clean these bushings, which are the only insulators that are cleaned at all on our system. The conducting spindle carries a current and therefore gets warm; its coefficient of expansion is different from that of porcelain, and any packing (such as cork) put in to make a joint will eventually give rise to a leak. It usually does so after a few months. What we really need is some new form of elastic joint that does not depend upon the elasticity of the jointing material. After a year or two cork joints on transformer bushings begin to disintegrate and trickle out. Whatever material is used it should be permanent, a quality which neither cork nor rubber possesses.

Mr. A. M. Robertson: In connection with the wet flash-over test of bushings (page 309), it is rather unsafe to assume the resistivity of the water used in this test to be 10 000 ohms per cm cube. The value must be accurately determined before any test is carried out on the bushing. Can the author give any further information regarding the accuracy of the figure in question? The whole matter of this test is made to appear much more simple than it is in actual practice; one has to determine the value of the resistivity of the water, and then to observe the angle and rate of precipitation. In a large-size bushing, some difficulty will be experienced in adjusting these factors over a large area. I think that the author might well have given fuller information regarding test practice.

Dr. J. L. Miller: It would have been interesting if the author had given us some impulse figures. I suppose that one difficulty in doing this would be the lack of information available, as very little has been published on the subject in this country up to the present. The author gives the impression that the only way a transformer can be damaged under impulse conditions is by breakdown of the major insulation, i.e. a fault between the h.t. and l.t. windings or to earth. He neglects the other type of breakdown which occurs between turns or between coils, and thus, on a system where the major insulation of the transformer is so designed that its breakdown voltage is greater than the flashover voltage V of one of the "weak link" bushings, surges whose maximum values are less than V may still cause the inter-turn type of breakdown, or even—as a previous speaker pointed out—cause breakdown of the major insulation due to the cumulative damaging effect of travelling waves. It is therefore my opinion that transformers may break down under impulse conditions even if they are designed to stand the 1-minute test for fully insulated transformers; other factors must be taken into consideration in their design. I should like to amplify the author's remarks regarding the property which condensers and choking coils have

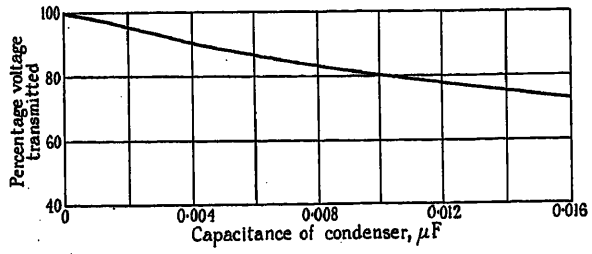


FIG. A.

of reducing the over-voltages passed on to transformers. The amount of amplitude reduction to be expected from the use of a practical and economical size of condenser and choking coil is not very great, and in this connection Figs. A and B have been prepared. They show the calculated reduction in the amplitude of a travelling wave for (Fig. A) condensers whose capacitances range in value from zero to 0·016 μF, and (Fig. B) choking coils whose surge inductances range from zero to 5 000 μH. The curves have been obtained from the

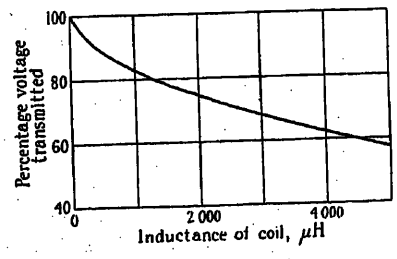


FIG. B.

maximum values of the families of transmitted-voltage curves given by

$$\frac{E}{0{\cdot}98 - 8{\cdot}7C}\left[e^{(-\,0{\cdot}05 \times 10^6 t)} - e^{(-\,5{\cdot}7 \times 10^3 t)/C}\right] - \frac{E}{0{\cdot}98 - 2{\cdot}56 \times 10^3 C}\left[e^{(-\,15 \times 10^6 t)} - e^{(-\,5{\cdot}7 \times 10^3 t)/C}\right]$$

and

$$\frac{E}{0{\cdot}98 - 7{\cdot}1 \times 10^{-5} L}\left[e^{(-\,0{\cdot}05 \times 10^6 t)} - e^{(-\,7{\cdot}0 \times 10^3 t)/L}\right] - \frac{E}{0{\cdot}98 - 2{\cdot}06 \times 10^{-2} L}\left[e^{(-\,15 \times 10^6 t)} - e^{(-7{\cdot}0 \times 10^3 t)/L}\right]$$

plotted as functions of C and L respectively, and the travelling wave on which the calculations were based rose to its crest value in 0·4 microsecond and fell away to half crest value in 14 microseconds. It will be seen that for a commercially-possible condenser capable of withstanding the high voltages which are likely to be

met, the reduction in amplitude is very little indeed, and for waves having longer backs than that which has already been considered (the cathode-ray oscillograph shows that longer waves do occur in practice) the amplitude reduction will be considerably less. The same remarks apply to the choking coil, although other important factors have to be considered in this case.

Mr. M. W. Singer: In spite of what some of the previous speakers have said in favour of the condenser type of bushing, I still believe that there is a great future for the all-porcelain multi-tubular type. The considerable amount of labour involved in dismantling the condenser-type bushing in the event of failure, in order to locate the fault, is an important factor which should be taken into consideration. On page 320 the author points out the dangers and disadvantages of filling with compound, and yet one or two pages afterwards he states that certain types of what he calls "all-porcelain" bushes are filled with compound. I am of the opinion that he has not heard of the type of all-porcelain bushing manufactured by Hermsdorf-Schomberg and Co., Germany, in which the interstices between the tubes of porcelain are filled with porcelain in the fluid state which afterwards hardens and forms one solid porcelain insulator. As regards the popularity of all-porcelain bushings, some valuable experience of their use has been obtained on the Continent over a number of years, and in the very severe winter of 1928–29 these bushings successfully withstood the extreme and abnormal temperature conditions. With regard to the rainfall statistics on page 332, I notice that Manchester is not included in the table. I do not understand why these figures of heavy rainfall were incorporated in the paper when such important factors as salt deposits, snow, fog, etc., were omitted. I am interested in the question of the production of an absolutely oil-tight joint. The author appears to get over the difficulty by making use of both cement and a gasket, evidently hoping that the deficiencies of one will be compensated for by the advantages of the other.

Mr. F. W. Taylor: The comprehensive way in which the author attacks the problem of bushing design, and the simple formulæ and curves given in the paper, make it appear at first sight that bushing design is a comparatively simple matter. For instance, on pages 312 to 314, formulæ are given for the potential gradients in various dielectrics on the assumption that the electrodes are concentric cylinders. Whereas this is true at some places in the bushing, there are other places where the assumption breaks down because there is a component of the field in an axial direction. Whilst this is not very important as regards porcelain, special care is necessary when dealing with laminated material, e.g. bakelite paper. Also critical gradients for air are rather indeterminate in enclosed places, and other factors such as the inconsistency and ageing of materials, and distortion of the field by deposits on the porcelain, all have their effect in nullifying theoretical assumptions. The author will no doubt agree that bushing design does not consist solely in the derivation or application of formulæ, valuable though they are; the important factor is the ability of the designer to determine how near the actual conditions in the bushing approach the ideal of the formulæ. Correlating the transformer insulation and bushing characteristics in the manner adopted by the author in the first part of the paper, would prove of no little value to the purchaser or consultant, and to the transformer manufacturer. In my opinion there is room for more investigation in this direction. When comparing the transformer and bushing insulation, however, the author does not make it quite clear whether he is referring to the major insulation (i.e. between winding and earth) or to the internal insulation between turns, layers, and coils. From the surge standpoint the latter is much the more important since the stresses between turns may be as much as 200 times normal, whilst the stresses to earth are of the order of 10 times normal. The amount of insulation necessary to protect against over-voltages due to surges therefore bears no simple relation to the test voltage on the transformer, and additional tests are necessary to correlate the strengths of the transformer and bushing insulation under transient conditions. In connection with the testing of bushings, I am surprised that the author makes no reference to the Schering bridge test. This is perhaps to be accounted for by the fact that he deals with porcelain and not with paper condenser bushings. The Schering bridge test is now recognized as of prime importance for most bushings in determining their quality before they are tested in the usual way, and also for ascertaining whether the voltage test has damaged them in any way. Unless a Schering bridge test is to follow, it is useless to test a bushing to an abnormally high voltage. Fig. 11 would be more valuable if the author stated the temperature and pressure of the air, whether it is enclosed or free, and the breakdown voltage of the oil in the standard test cell. As regards the question of puncture voltage (page 314), irregularities in the conductor, dust, etc., will encourage the formation of streamers when the air breaks down thus presenting needle-point electrodes to the porcelain instead of a cylinder of radius r_2. Under these conditions breakdown of the porcelain will occur much earlier. A bushing which the author has omitted to mention, and which is really a hybrid of the oil-filled and the condenser types, is the oil-filled condenser bushing consisting of dry paper insulation having foils wound in the usual manner of condenser bushings, the whole being impregnated in oil. This type has all the valuable properties of the oil-filled cable as regards reliability, power factor, smallness of dimensions, etc., without the disadvantages of bakelized paper.

Further Contributions to the Discussion.

Mr. A. O. Austin (*communicated*): In this discussion of the paper it is assumed that the scope of the latter is such that it is impossible to cover the various types of construction in sufficient detail to allow for material departure from present practice. Many factors are involved in the design and construction of bushings, so

that a discussion must usually be limited to a definite size and type, otherwise contradictory results might be cited, tending to disprove observations which might be correct for another size or a slight modification of the bushing. The effective insulation of transmission lines has increased materially in most parts of the world during recent years. This has necessitated much higher flash-over values for bushings than those shown in Table 8. The flash-over value of the bushings at normal

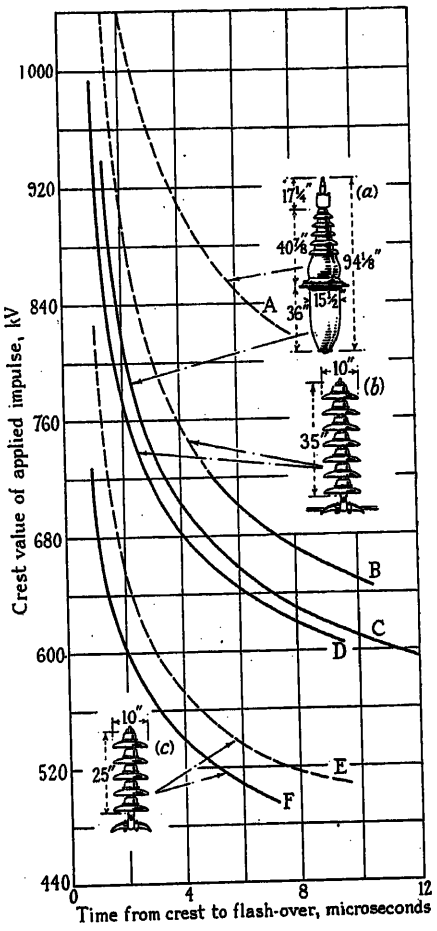


FIG. C.—Impulse-voltage/time-lag characteristics.

Curve A. Negative impulse test on bushing (*a*).
Curve B. Negative impulse test on insulator string (*b*).
Curve C. Positive impulse test on bushing (*a*).
Curve D. Positive impulse test on insulator string (*b*).
Curve E. Negative impulse test on insulator string (*c*).
Curve F. Positive impulse test on insulator string (*c*).

frequency is usually not so important as the relative time-lag for bushings and other station insulation under a high-voltage transient. Under an impulse voltage the relative characteristics of the bushing and other insulation may vary considerably from those indicated by the arcing voltage at normal frequency. Fig. C shows the impulse-voltage/time-lag characteristics of a 110/140-kV oil-filled bushing insulator and two suspension insulators, for impulses which rise to the crest value in ¼ microsecond and then fall to half the crest value in 100 microseconds. The desire to use a small diameter and to avoid radio interference has led to the almost total abandonment of bushings employing a zone of air for insulation, except for a lower voltage. One objection to using an air zone is that under a transient the air zone breaks down, robbing the bushing of a large part of the insulation just when it is most needed. The filling of a space by oil or compound, as indicated by the author's curves, is to be preferred. This gives rise to a material increase in the flash-over voltage, as indicated by Fig. 22. The advantage of placing a ring-type current transformer inside the bushing case is very material, particularly where the insulation is brought up over the current transformer. Used in this way, the lower end of the bushing is provided with much more insulation, a particularly valuable feature in circuit-breaker work. With this arrangement a larger diameter of the porcelain member may be used for the lower end, thus reducing the intensity of the electrostatic field. This is important, as a strong electrostatic field due to a small diameter or short length in the insulating member will tend to cause conducting matter to be precipitated and flash-over to occur in operation, even though the bushing may apparently have an ample factor of safety under test conditions. The increased insulation also reduces the danger of a hot pocket of gas shunting the insulating surface and causing a short-circuit. While the above applies to circuit breakers, the same type of construction is particularly applicable to bushings used with transformers in which there is considerable space above the oil, as it enables the lower end of the bushing to be made much shorter without danger of a discharge occurring over the surface. As explained by the author, bushings equipped with a wound primary for the current transformer are being used where conditions are unusually difficult. Bushings of this type have been produced having a number of ratios for the current transformer ranging from 25:5 up to 400:5 amperes. This range would be exceedingly difficult to provide for in an ordinary type of current transformer with a bushing having a flash-over voltage of 475 kV. In addition to the current transformer, the bushing is provided with a capacitance tapping. The coupling plate for this is placed between the current-transformer secondary and the main core of the bushing. Owing to the large amount of energy available from a wound-primary current transformer, it is possible to design such a transformer so that it has a good output even for small currents. Phase-angle and ratio corrections can be made over a wide range of current in the primary by the use of series or shunt impedance, which may be applied to either primary or secondary. The capacitance coupling method was used some years ago for voltage indication and synchronizing, and more recently it has been widely used for relay operation. As the author remarks, the use of the capacitance tapping for obtaining a voltage eliminates the hazard of a potential transformer and tends to give much greater reliability. The use of the capacitance coupling for metering is subject to certain limitations. Normally the voltage obtained from a capacitance coupling with a step-down transformer has an angle of lead of 60° or 80°. It is, of course, possible by the use of shunt or series impedances to bring the voltage of the capacitance coupling into phase with the voltage of the high side. In general, however, the voltage may be taken from one of the other phases, so that only a

small phase-angle correction is necessary. It is evident that the characteristics of the capacitance coupling will be entirely different from those of a potential transformer, and unless this is recognized errors may result if either is used for metering purposes. Improvements in wave-form materially reduce the error. On some systems it is possible, by applying a factor or adjusting the coupling, to use the capacitance coupling for metering purposes. While the general use of the capacitance coupling for such purposes may be questionable, there are many applications where a high degree of accuracy is not necessary and which will not warrant the installation of potential transformers, owing either to the increased cost or to the greater hazard. The use of the capacitance coupling for load dispatching or telemetering installations is another application of bushings equipped with internal current transformer and capacitance couplings. While there are certain limitations as to the capacitance coupling, it seems that the development of the internal current transformer with wound primary would make it possible to improve station design. The large output which may be obtained regardless of the current in the primary and the high voltage involved, makes it possible to use additional apparatus which would overload a current transformer of the ring type. By using a considerably higher voltage on the secondary the size and cost of the leads can be greatly reduced. This is particularly important where the switchboard or control apparatus is located at a distance from the current transformer. The internal current transformer having a wound primary has a particular application for interconnections where the current may vary over a wide range and may even reverse. The improved metering equipment for points of interconnection will enable interconnections to be made to advantage which are practically out of the question at present, owing to the cost of metering at a high voltage. The voltage gradient over the surface has much to do with the relation between the dry and wet arcing voltages for the bushing. A bushing with a rather poor stress distribution may have its gradient so improved in the rain or wet test that the flash-over voltage when wet will be approximately the same as, or even higher than, that when dry. This is particularly true where the artificial rain and conditions are such that the surface of the bushing will not become hot. It must be remembered that the charging current is materially in advance of the voltage, and that an appreciable drop in voltage may be developed over wet surfaces. The wet flash-over voltage is therefore not necessarily a function of the so-called wet "striking distance" for most designs. In fact, many bushings will give a higher wet flash-over voltage when the wet striking distance is reduced so as to prevent over-stress or "priming" of a zone which is carrying too high a voltage. In general, high wet flash-over voltages are more easily obtained with bushings having small flanges. The loss due to surface leakage, however, is generally higher with bushings of this type at normal operating voltages. A small heating element placed inside the shell of an oil-filled bushing will greatly reduce the leakage losses and improve the reliability of the bushing where it is likely to be subjected to severe fogs, salt, or dirt. Numerous types of bushings which have been successfully used over a period of years are likely to cause radio trouble and therefore cannot be employed at the present time in many districts. For some years manufacturers have been gradually increasing the flash-over voltages of bushings in order to prevent interruptions. Higher flash-over voltages will undoubtedly be used as means are found to increase the ability of apparatus to withstand high-voltage transients. Bushing specifications should be given careful consideration, as a severe specification may result in a poor design. Some designs of bushings which can withstand very severe transients will fail at a comparatively low voltage in a normal-frequency test where the voltage is applied for a length of time sufficient to cause breakdown due to a pyro-electric effect over the surface. A specification calling for a very high wet flash-over voltage may result in a bushing which has higher losses under conditions of rain at the normal operating voltage. Specifying an unnecessarily high current-carrying capacity in the bushing, or the application of a very high voltage for a considerable length of time, may necessitate the use of a larger diameter of lead, which will increase the gradient or surface stress on the outside of the bushing. This may make it necessary to use a larger or more expensive bushing without any improvement for operating conditions. One of the greatest difficulties in the design or manufacture of bushings, particularly those of large size, is to prevent cracking under operating conditions owing to differential expansion between the dielectric and the metal, or to shock in the case of circuit breakers. During the last 3 years bushing design has been so improved that the ability to withstand shock and thermal stresses is such that not a single large-size bushing has been lost, either in shipment or in operation, by the company with which I am associated. As the above applies particularly to circuit-breaker bushings having net weights from 1 500 to 2 500 lb., designed for operating voltages from 196 to 220 kV, it will be seen that the problem of building and shipping smaller and lighter bushings is easy nowadays compared with what it was a few years ago.

Dr. Eng. H. von Treufels (*communicated*): In regard to the relation of the flash-over voltage in oil to the flash-over voltage in air the author states that for smooth porcelain a factor of 2·5 should be applied, and that this factor should be a trifle higher for ribbed porcelain. This agrees with my experience. For purposes of calculation I generally employ a factor of 3. It is, moreover, customary in Germany to fix the flash-over voltage in air of the oil end of the bushing at 200 per cent of the working voltage. I agree with the author that the dry flash-over voltage depends upon (*a*) the dry flash-over distance, (*b*) the radial dimensions of the bushing, and (*c*) the nature of the dielectrics. I would point out that according to Toepler the "gliding spark voltage" ("Gleitfunkenspannung") at which short, blue, gliding discharges appear, may be computed from the formula

$$E_g = 74 \cdot 8\,(d/\kappa^{0 \cdot 44})$$

where d = thickness of insulating sheath, and κ = specific inductive capacity of insulating material. This calculation seems to me of importance inasmuch as the dry flash-over voltage may be adversely affected

by an essentially lower gliding spark voltage. The formula is very useful to the designer of multi-tubular bushings incorporating the condenser principle, as it enables him to satisfy himself that a normal relation exists between the thickness of the porcelain and the length of the bushing. For such bushings the gliding spark voltage of the entire bushing is easily calculated as it represents the sum of the gliding spark voltages appertaining to the separate cylinders or tubes. The curves reproduced in the author's Fig. 21 agree with the results of our investigations. In regard to the problem of oil-tight bushings, it is possible to construct the gaskets without using cement. For this purpose the porcelain parts require to be provided with bevelled shoulders at their flange ends, serving as seats for gasket and flange. In Fig. D(*a*) I have combined the gasket designs of Figs. 26 and 27 with the cementless type mentioned above. Investigations are now being made into the question whether cork linoleum or klin-

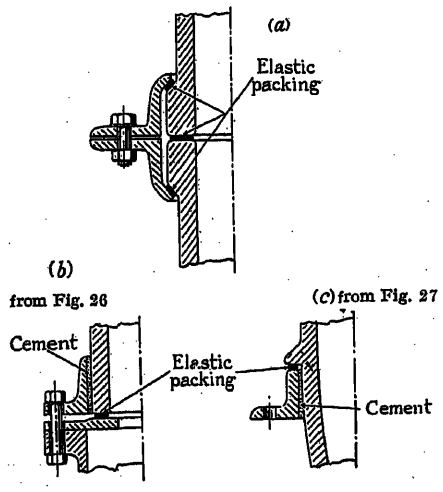


FIG. D.

gerite is the more suitable for packing purposes. The following are the unique advantages of all-porcelain multi-tubular bushings embodying the condenser feature. (i) No oil or explosive insulating material used. (ii) Smaller diameter of bushing. (iii) Minimum height of insulator part in consequence of favourable distribution of stress. (iv) Porcelain only employed as insulating material: no cementing material used. (v) Simple and clear calculation of the stress to which the separate parts are subjected. (vi) Insulation divided into separate elements, thus enhancing reliability of the bushing in service. (vii) Preliminary test of the separate cylinders or tubes can be made by subjecting them to over-voltages. (viii) Possibility of making direct connection between measuring devices and the layers or deposits on the surface of the porcelain. (ix) Maximum mechanical resistance to bending and axial pressure. (x) Simple mounting. Improvements in manufacturing methods and further practical experience will greatly enhance these advantages.

Mr. W. J. John (*in reply*): I agree with Mr. Norris that the present design and construction of bushings are based on operating experience rather than on fundamental principles, and I have attempted in the first part of the paper to do something to improve this state of affairs. The great difficulty, as Mr. Norris points out, is in allowing for the effect of surges due to lightning and other causes. He is of opinion that bushings should be identical whether the transformer insulation is graded or not; although I must confess to a considerable degree of sympathy with this point of view, I believe that on the whole a better procedure is that advocated in Table 9, where different characteristics are suggested, depending upon whether or not the insulation is graded. The 1-minute tests are different for the two types, and hence the bushing characteristics associated with them are also different. By a correct choice of line-insulation characteristics (see page 304) it is possible to reduce the magnitude of the incoming surges to a value which the graded-insulation bushing can withstand, thus enabling a cheaper bushing to be employed. While this may become important at the higher voltages, say 66 kV and above, up to 33 kV I agree with Mr. Norris that all bushings should be identical whether their transformers have graded insulation or not: the saving in cost is not sufficiently important to overcome practical objections to increasing the number of standard bushings. Mr. Norris's discussion of the different surge breakdown characteristics of air and solid insulation is valuable. I do not agree with his statement that the $\frac{1}{2}$ microsecond which elapses before a reflected wave causes flash-over at the nearest line insulator is so short that no damage results. Its possible effect on the solid insulation is pointed out by Mr. Norris himself earlier in his contribution.

Mr. Ashley is disappointed because I have given little information regarding the condenser-type bushing (page 318). The design and construction of this type are so distinctive that any attempt to deal with them adequately would have made the paper unduly long. I should like to make it perfectly clear, however, that I in no way disparage or undervalue condenser bushings. The paper makes fair statements regarding the relative advantages and disadvantages of this type of bushing, and none of these statements can be correctly classed as "unfortunate." Whereas condenser-type bushings have given trouble in the not far-distant past, trouble with oil-filled bushings has been very rare: I do not agree that the past record of condenser-type bushings of all makes is as good as that of oil-filled bushings. The modern condenser-type bushing is, however, an excellent product, and the operating record of an average bushing of this type will in the future probably be as good as that of an average bushing of any competitive type. The statement in the paper regarding the relative costs of the different types is a generalization, and I agree with Mr. Ashley that the comparison may be affected when extra features are included. It is true that the safety of the oil-filled bushing depends upon the oil remaining in the porcelain top and bottom shells, and the function of the gauge glass is to afford visible indication that the oil is so remaining. Any leakage which may occur will be very slow, and the fall of the oil-level should be noticed in ample time to prevent any damage. What Mr. Ashley claims for the broken porcelain rain-sheds of a condenser-type bushing can

be claimed even more positively for a leaky oil-filled bushing; with a slow leak "the bushing would still operate satisfactorily and thus allow time for alternative supply arrangements to be made." His queries regarding Tables 20 and 22 have been answered in the reply to Mr. Abell's contribution to the London discussion (see page 333). The use of the word "paxolin" in the paper must be regarded as a convenient abbreviation of "synthetic resin varnish-treated paper." It is pointed out on page 311 that paxolin is taken as being representative of this type of insulation.

Mr. Fennell's remarks are particularly valuable as coming from a user rather than from a manufacturer. His experience with oil leaks is, I believe, shared by many users of outdoor transformers having conservators. This trouble is being given careful attention by manufacturers, and a bushing can be produced which is completely oil-tight at both the flange and the top cap surrounding the centre conductor. The great trouble is that so many factors are involved that it appears to be impossible to obtain by a reasonably simple commercial method a joint which is consistently oil-tight. Of 12 joints made by commercially identical processes, 10 may be good and 2 bad. A further hazard is introduced by the stresses placed on the joints in the process of connecting the leads to the completed bushing. I agree with Mr. Fennell that a metal ring cemented to the insulator is the proper medium for connecting the bushing to the transformer tank. As stated in my reply to Mr. Norris, I also agree that up to 33 kV no distinction should be made in the bushing whether its transformer has an earthed or an insulated neutral.

I support Mr. Robertson's opinion that any assumption as to the resistivity of the water used in the wet flash-over tests is dangerous. The resistivity should always be checked, and simple instruments are obtainable for measuring it quickly and accurately. Full details of wet tests are given in several specifications.*

The question of impulse figures raised by Dr. Miller is very interesting, and much information regarding it is accumulating as a result of modern research work. Much still remains to be cleared up, however, and agreement has not yet been reached concerning such important matters as the shape of the impulse wave experienced in practice and how far laboratory tests made by means of surge generators and cathode-ray oscillographs actually reproduce any desired wave-shape. I agree with Dr. Miller that the question of the effect of surges on the inter-turn insulation as distinct from the major insulation is important, and his opinion that transformers may break down under impulse conditions even if designed to stand the 1-minute test for fully insulated transformers shows the importance attaching to a study of this matter. I return to this subject in my reply to Mr. Taylor. I thank Dr. Miller for including in his contribution to the discussion an account of some valuable work on the effect of inductances and condensers in reducing over-voltages.

Mr. Singer believes in the future of the all-porcelain multi-tubular type of bushing. While this is undoubtedly an excellent type, it becomes heavy and costly for voltages much in excess of 66 kV (see Fig. 38). The all-porcelain multi-tubular bushing incorporating the condenser principle retains all the advantages of the plain multi-tubular type and very considerably reduces its disadvantage of excessive bulk. Regarding compound filling, this is perfectly satisfactory provided the correct kind of compound is used and a certain technique is adopted. I am not acquainted with the type of all-porcelain bushing manufactured by Hermsdorf-Schomberg and Co., in the manufacture of which porcelain in the fluid state is used, and I therefore cannot express any opinion concerning it. The figures of heavy rainfall were included in the paper because of all the atmospheric conditions which affect bushing performance rain was the only one for which information was available in statistical form. Appendix IV justifies the rate of precipitation used for the artificial rain tests in Section 2.

I am in complete agreement with Mr. Taylor's summary of the reasons for exercising caution when attempting to design a bushing from formulæ and curves. Mr. Taylor, like Dr. Miller, draws attention to the necessity for distinguishing between major insulation and internal insulation. The formula (page 303) connecting surge strength of complete transformer and 1-minute transformer test is based on operating experience and therefore deals with the transformer insulation as a whole, both major and internal. It assumes that the internal insulation of transformers tested to the 1-minute test values specified in B.S.S. No. 171—1927 follows normal practice, since the formula is, of course, a generalization. Regarding Schering bridge tests, these were not included because—as Mr. Taylor suggests—the paper does not deal in detail with condenser-type bushings, and it is only for these that the Schering bridge has been used commercially. The electric strengths of air and oil given in Fig. 11 are taken from results obtained by Peek. The air under test was enclosed between concentric cylinders open at both ends. The temperature was 25° C. and the pressure 76 cm of mercury. When tested between standard discs 0·5 cm apart the oil withstood 58 kV (max.) at 25° C. The effect on the puncture voltage of the various factors mentioned by Mr. Taylor is allowed for because the values for the electric strength of porcelain tubes were actually obtained by tests on bushings. These bushings were tested when made for ordinary operating conditions and so, if preferred, the equations used for the determination of puncture voltage (see page 314) may be regarded as empirical, $g_{max.}$ being obtained from analysis of test results. The "hybrid" oil-filled condenser-type bushing is interesting, but it is not described in the paper because details of condenser-type bushings are omitted.

Mr. Austin's contribution is particularly welcome, seeing that it comes from a leading American authority who has had unrivalled experience of high-voltage insulation problems. I am particularly interested in the information he gives concerning the use of wound-primary current transformers and capacitance tappings.

Dr. von Treufels makes a number of interesting remarks as to German practice. He sets out very fairly the claims of the multi-tubular all-porcelain bushing incorporating the condenser principle of construction. In my opinion this type of bushing has much to commend it.

* See, for example, B.S.S. No. 223—1931, p. 12.

AN EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF EARTHED RECEIVING AERIALS.*

By F. M. COLEBROOK, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received 25th June, 1931, and in final form 15th January, 1932.*)

SUMMARY.

The paper is concerned with the behaviour of earthed open-aerial receiving systems. The analysis of such systems is based on the classical transmission-line equations, as modified by Moullin to apply to distributed excitation.

Part 1 gives the theoretical formulæ so obtained for the case of a plain aerial with uniformly distributed constants, and the detail of the variation with frequency of the resistance and reactance components of the effective impedance of such an aerial.

It is shown that successive resonances (i.e. conditions of zero reactance) are given by an equation of the form

$$\lambda = (4h/n)(1 + Ah^2)$$

where n is any integer and A is a small factor depending on n and on the attenuation constant of the aerial considered as a transmission line. The corresponding values of the resistance are shown to be $Rh/2$ (approximately) when n is odd, and a very high value when n is even, R being the total effective resistance per unit length of the aerial.

The actual variation of the impedance of a plain uniform aerial as a function of frequency was determined experimentally, and a detailed analysis of the results in relation to the theory is given.

The observed variations of resistance and reactance are shown to be in substantial agreement with those deduced from the analysis, but it appears that the actual length of the aerial (h) must be replaced by an effective length $h + \varepsilon$, ε being about 5 per cent of h. This is in agreement with a more rigid analysis by Abraham, and with experimental results obtained by Wilmotte. The observed aerial resistance was found to be mainly due to parasitic eddy-current and dielectric losses. It was reduced to less than one-third of its value by using a single-wire "earth screen."

The validity of the fundamental assumptions, to a useful degree of approximation, having been established by measurement, Part 2 of the paper is devoted to obtaining additional information by purely analytical methods. The analysis is mainly based on the case of a plain aerial divided into three parts in each of which a uniformly distributed e.m.f. is assumed to be induced, the intensities being different in the three parts.

By an analytical manipulation of this three-part case a line integral formula is found for the effective e.m.f. induced in a uniform aerial by a non-uniform field (Section 7). The variation of the effective e.m.f. induced by a uniform field is considered as a function of frequency and aerial height, and it is shown that no advantage is gained by making $h > \lambda/4$ unless certain parts of the aerial are compressed (Section 8).

The relative effectiveness of different parts of a receiving aerial is considered in Section (9), and it is found that in an L aerial short compared with the wavelength the addition of a down-lead from the open end nearly to the ground may actually increase the total effective e.m.f. in spite of the reversed e.m.f. induced in the added length.

An earthed aerial of this shape with the vertical members of length $\lambda/4$ and the horizontal member of length $\lambda/2$ is shown to have a figure-of-eight polar diagram with a law of the form $\cos(\frac{1}{2}\pi \cos\theta)$ (Section 10).

The effective e.m.f. formulæ of the three-element case are applied to the Franklin suppressed half-wave construction and afford means of allowing for the effect of aerial resistance in this system (Section 11).

In Section (12) the effective e.m.f. of the present formulation is related to the original conception of "effective height." It is suggested that the idea of "effective height" is one which has to a great extent outlived its usefulness.

The analysis of a receiving aerial considered as a collector of energy from the incident wave is given in Section (13). The figure of merit from this point of view is $|e_\theta|^2/R_\theta$, which is determined as a function of h and λ. It reaches a maximum when h is very approximately $\lambda/4$, and thereafter oscillates with rapidly diminishing amplitude. Considered as a collector of energy the suppressed half-wave construction will not apparently give an increase in useful power proportional to the increase in height, owing to the corresponding increase in R_θ.

Current and potential distributions in receiving and transmitting aerials are discussed in Section (14). It is shown that they depend on the distribution of the exciting field, and that the current distribution in a receiving aerial may be totally different from that in a transmitting aerial of the same height. Current nodes in a receiving aerial may be any distance apart from 0 to λ, and are not necessarily separated by half a wavelength as in a transmitting aerial with a point source of excitation.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

Part I.

(1) INTRODUCTION.

The author has given in an earlier paper* an analytical discussion of the behaviour of a receiving aerial, this paper being an extension and generalization of a paper by E. B. Moullin† on the same subject. A further degree of generalization was arrived at by R. M. Wilmotte.‡ Various formulæ for the effective resistance and reactance of a receiving aerial were given in these papers, and also formulæ for the effective height of the aerial under various conditions. A more general result was also deduced analytically and confirmed by experiment,

* See Bibliography, (1). † *Ibid.*, (2). ‡ *Ibid.*, (3).

namely, that the current at the base of a receiving aerial could be represented as the vector quotient of an effective e.m.f. divided by the vector sum of the tuning-circuit impedance and an effective aerial impedance. It was shown that the latter would be independent of the distribution of e.m.f. in the aerial and could therefore be determined by measurements made with a locally induced e.m.f.

Since the above papers were written a method of measuring resistance and reactance at radio frequencies has been developed at the National Physical Laboratory.* The method is very conveniently applicable to the measurement of aerial impedance and it was decided to make measurements on a small receiving aerial with a view to finding out how closely the simple transmission-line equations that had been used in the analysis represented the actual state of affairs. At the same time the analytical side of the subject was further extended, particularly with a view to arriving at a practical general formula for the effective e.m.f. induced by a non-uniform field, and also to arrive at some knowledge of the current distribution in an aerial under transmission and reception conditions. The paper records the progress made in these directions.

(2) Analysis of the Variation with Frequency of the Impedance of a Plain Aerial.

This subject has already been considered to some extent in the earlier paper referred to in the first Section, but the most important features will be re-stated here for convenience of reference, and developed in a form suitable for experimental verification.

The aerial is assumed to have a uniform resistance, inductance, and capacitance per unit length, represented by the symbols R, L, and C. This assumption is obviously open to question both as to the uniformity and to the precise significance of the symbols R, L, and C. The question of significance need not be considered at this stage. It will be sufficient for present purposes to consider the symbols as being virtually defined by the differential equations in which they appear—to regard them, that is to say, as the coefficients of the " in phase " and " in quadrature " potential differences assumed to exist in the differential elements of the conductor. These coefficients will be assumed uniform because it is one of the objects of the investigation to find to what extent this assumption, known to be inexact but without which the equations are practically impossible to solve, is a sufficiently close approximation to be useful.

The aerial is assumed to be of total length h and to be connected to earth through an impedance Z_0. It is situated in an electric field the precise configuration of which need not be specified at this stage, beyond stating that its variation with time is sinusoidal, with pulsatance ω. As shown in the earlier paper, the current at the base of the aerial can be represented in the vector form

$$i_0 = \frac{e_e}{Z_0 + Z_e} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where e_e is an effective e.m.f. depending on the constants and configuration of the aerial and of the field, and Z_e is an effective aerial impedance which is independent of the field and is thus a characteristic of the aerial alone. For the present we shall be concerned only with this quantity Z_e. It is of the form

$$Z_e = Z \coth Ph \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $$P^2 = j\omega C(R + j\omega L) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and $$Z = P/(j\omega C) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Writing $P = \alpha + j\beta$, the components α and β depend on the constants L, C, and R as follows. If $R^4/(\omega^4 L^4)$ be neglected compared with 1

$$\alpha = \frac{R}{2}\sqrt{\left(\frac{C}{L}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and $$\beta = \omega\sqrt{(LC)}\left(1 + \frac{R^2}{8\omega^2 L^2}\right) \quad . \quad . \quad . \quad (6)$$

If in addition $R^2/(8\omega^2 L^2)$ is negligible compared with 1, we have the simpler result

$$\beta = \omega\sqrt{(LC)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Under the conditions of the second approximation, if

$$Z = a + jb \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

then $$a = \left(\frac{L}{C}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and $$b = -\frac{R}{2\omega\sqrt{(LC)}} \quad . \quad . \quad . \quad . \quad (10)$$

The separation of Z_e into its resistive and reactive components R_e and X_e presents no difficulty. It gives

$$R_e = \frac{R}{2\alpha\beta} \cdot \frac{\beta \sinh 2\alpha h - \alpha \sin 2\beta h}{\cosh 2\alpha h - \cos 2\beta h} \quad . \quad . \quad (11)$$

$$X_e = \frac{1}{\omega C} \cdot \frac{\alpha \sinh 2\alpha h + \beta \sin 2\beta h}{\cosh 2\alpha h - \cos 2\beta h} \quad . \quad . \quad (12)$$

The above are exact formulæ. In making any approximations some care must be exercised. It is true that αh is small in many, if not most, practical cases, but the βh terms vanish periodically, so there will always be regions where the αh terms, small though they may be, are the principal factors. Further, it will be apparent from the consideration of actual magnitudes in a later Section that there will be many cases where the αh terms are not negligible compared even with the maximum values of the other quantities. With these reservations, however, we can form some idea of the general character of the variation of R_e and X_e with frequency by assuming that $\alpha^2 h^2$ is small compared with 1, so that $2\alpha h$ can be written for $\sinh 2\alpha h$ and 1 for $\cosh 2\alpha h$. Then

$$R_e = Rh\frac{2\beta h - \sin 2\beta h}{2\beta h(1 - \cos 2\beta h)} \quad . \quad . \quad . \quad (13)$$

except when $\cos 2\beta h$ is in the neighbourhood of unity. Thus, apart from the variation of R itself with frequency, R_e will vary with frequency in the manner of the function

$$\frac{\theta - \sin\theta}{\theta(1 - \cos\theta)}$$

* See Bibliography, (4).

which is shown plotted in Fig. 1. (The infinities of this function are regions where the approximation is no longer valid.) The observed variation of R_e is of this character, but, as will appear later, it is complicated by the fact that R itself increases with frequency. It should be noted that the function has the limiting value $\frac{1}{3}$ when $\theta \to 0$, corresponding to the fact that R_e tends to the limit $Rh/3$ when the aerial is small compared with the wavelength.

In a similar manner the expression for X_e can be approximated to

$$X_e = -\frac{1}{\omega C h} \cdot \frac{\beta h \sin 2\beta h + 2\alpha^2 h^2}{1 - \cos 2\beta h + 2\alpha^2 h^2} \quad . \quad . \quad (14)$$

and except in the region where $1 - \cos 2\beta h$ is nearly zero, this approximates very closely to

$$X_e = -\frac{1}{\omega C h} \cdot \beta h \cot \beta h = -\sqrt{\left(\frac{L}{C}\right)} \cot \beta h \quad . \quad (15)$$

Thus the general character of the variation of the

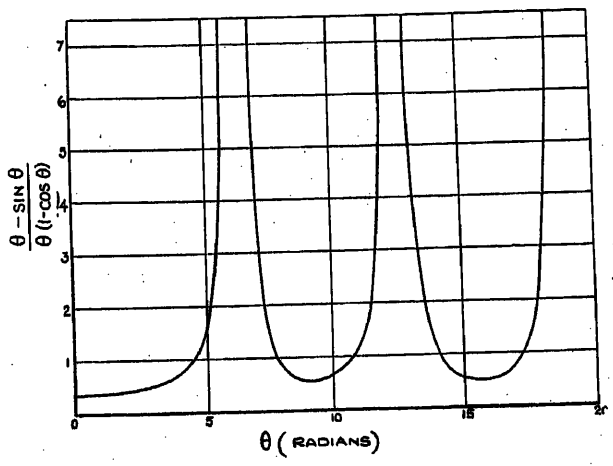


FIG. 1.

reactance is that of the variation of $-\cot \frac{1}{2}\theta$, using θ in the same sense as above, but the effect of the resistance terms is to convert the $\pm \infty$ discontinuities into a very steep variation between finite limits. The variation is illustrated pictorially in Fig. 2. The observed variation of X_e is known to be of this character.

The critical values of X_e and R_e will now be examined in more detail for comparison with observed values.

(3) DISCUSSION OF CRITICAL VALUES OF AERIAL RESISTANCE AND REACTANCE.

(a) *The Resonance or Zero-reactance Conditions.*

Since

$$X_e = -\frac{1}{\omega C} \cdot \frac{\alpha \sinh 2\alpha h + \beta \sin 2\beta h}{\cosh 2\alpha h - \cos 2\beta h}$$

the condition for zero reactance is

$$\alpha \sinh 2\alpha h + \beta \sin 2\beta h = 0 \quad . \quad . \quad . \quad (16)$$

No exact explicit solution is obtainable in general terms, but the solution is obviously of the form

$$2\beta h = n\pi + \theta \quad . \quad . \quad . \quad . \quad (17)$$

where θ is small and n is any integer. The assumption that θ is small leads by ordinary methods to the solution

$$\theta = (-1)^{n+1} \frac{4\alpha^2 h^2}{n\pi} \quad . \quad . \quad . \quad . \quad (18)$$

giving as the values of βh corresponding to zero reactance

$$2\beta h = n\pi \left\{1 + (-1)^{n+1} \frac{4\alpha^2 h^2}{n^2\pi^2}\right\} \quad . \quad . \quad (19)$$

It will be convenient to express β in terms of λ. For this purpose we have, from the definition of α and β,

$$\beta^2 = \omega^2 LC + \alpha^2 \quad . \quad . \quad . \quad . \quad (20)$$

If we now assume that the velocity of electric waves along a resistanceless wire is the same as that in free space, we have

$$\omega^2 LC = 4\pi^2/\lambda^2 \quad . \quad . \quad . \quad . \quad (21)$$

so that

$$\beta = \frac{2\pi}{\lambda}\left(1 + \frac{\alpha^2\lambda^2}{8\pi^2}\right) \text{ very approximately} \quad . \quad (22)$$

By a simple process of successive approximation we can obtain as the resonance or zero-reactance relations between h and λ

$$\lambda = \frac{4h}{n}\left(1 - \frac{2\alpha^2 h^2}{n^2\pi^2}\right) \text{ when } n = 1, 3, 5, \text{ etc.} \quad . \quad (23)$$

$$= \frac{4h}{n}\left(1 + \frac{6\alpha^2 h^2}{n^2\pi^2}\right) \text{ when } n = 2, 4, 6, \text{ etc.} \quad . \quad (24)$$

The odd values of n correspond to the ordinary $\frac{1}{4}$ wavelength and $\frac{3}{4}$ wavelength resonances (points P_1 and P_3 in Fig. 2). The even values of n correspond to the zero reactance points at the centre of the steep variation between the apparent discontinuities (points such as P_2 in Fig. 2). Thus the reactance is not infinite or very large when the height is half a wavelength, but is actually zero, with very large positive and negative values on either side of this condition. The impedance, however, is very large in this region, since R_e is very large.

It will be shown later that the correction terms in the above resonance relations are, in general, very small—parts in a thousand only. The observed differences between λ and $4h/n$ will be found to be due to another cause and not the inherent resistance correction given above.

It is again emphasized, however, that in spite of the smallness of the correction terms they must be taken into account when the variations of the impedance and the effective e.m.f. under resonance conditions are being considered, for at certain of the resonances the variation with frequency is so rapid that the small correction terms are actually the decisive and important ones. This is, of course, a general observation applicable to all analyses of resonances. Though the effect of the resistance terms may in general be negligible they become

the principal determining factors in the neighbourhood of resonant conditions, so that any analysis of the behaviour of receiving aerials which neglected the resistance terms would be useless in relation to some of the most interesting and important features of the problem.

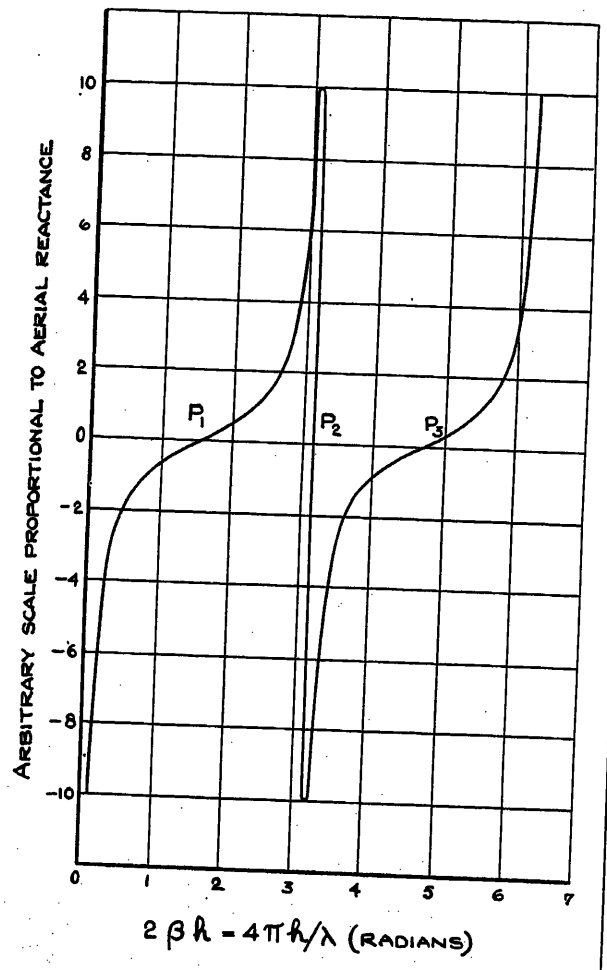


FIG. 2.

Certain other particular values of the reactance are of interest, namely those for which

$$2\beta h = (2n + 1)\pi/2$$

or

$$h = (2n + 1)\lambda/8$$

For these points, assuming that $2a^2h^2$ is negligible compared with 1 and βh,

$$X_e = \pm \frac{\beta h}{\omega C h} = \pm \sqrt{\frac{L}{C}} = \pm \frac{1}{C \times 3 \times 10^{10}} \quad . \quad (25)$$

These points are therefore convenient for determining the apparent value of C, the capacitance per unit length. Another condition useful for this purpose is given by

$$Ch = -\lim_{\omega \to 0} \frac{lt}{\omega X_e} \quad . \quad . \quad . \quad . \quad (26)$$

(b) Critical Values of the Effective Resistance.

In general

$$R_e = \frac{R}{2a\beta} \cdot \frac{\beta \sinh 2ah - a \sin 2\beta h}{\cosh 2ah - \cos 2\beta h}$$

Some interest attaches to the values of R_e corresponding to the resonant frequencies considered in the preceding Section. In the case of the quarter wavelength resonances, R_e is not varying very steeply with frequency, and the approximation $\lambda = 4h/n$ can safely be used. This corresponds to $2\beta h = n\pi$, $n = 1, 3, 5$, etc., and gives

$$R_e = \frac{R}{2a\beta} \cdot \beta \cdot \frac{\sinh 2ah}{1 + \cosh 2ah} \quad . \quad . \quad (27)$$

$$\approx \frac{Rh}{2} \text{ if } a^2h^2 << 1$$

In the case of the half- and full-wave resonances R_e is varying very rapidly with frequency and is very large. An exact solution can be carried out by substituting the relevant resonance condition in the general formula for R_e, but it leads to a complicated result which cannot safely be approximated.

Other convenient particular values are those corresponding to

$$h = (2n + 1)\lambda/8 \ (n = 0, 1, 2, 3, \text{etc.})$$

which give for $h = \lambda/8$

$$R_e \approx Rh(1 - 2/\pi) \approx 0{\cdot}36Rh \quad . \quad . \quad (28)$$

and for $h = 3\lambda/8$

$$R_e \approx Rh(1 + 2/\pi) \approx 1{\cdot}21Rh \quad . \quad . \quad (29)$$

etc.

where a^2h^2 is neglected by comparison with 1. Finally, when $\beta h \to 0$, i.e. when the aerial is short compared with the wavelength,

$$R_e \to Rh/3 \quad . \quad . \quad . \quad . \quad . \quad (30)$$

(4) Measurement of the Effective Impedance of a Typical Small Receiving Aerial.

Measurements were made of the impedance between the aerial and earth terminals of a plain aerial of 3/19 S.W.G. copper wire having a total length of 38·6 m (about 127 ft.) from free end to earth. The aerial consisted of two parts, a horizontal part about 29 m long at a height of about 7·5 m, the remainder of the length being in a sloping lead to earth. The aerial and earth leads were brought in through the wall of a wooden hut running parallel to the horizontal part of the aerial. The length of the earth lead (included in the total length given above) was about 2·5 m. The earthing system consisted of a line of buried copper plates running along the foot of the wall of the hut.

The impedance of the aerial with respect to an e.m.f. applied between the aerial and earth terminals was determined in the form $R_e + jX_e$ by the methods described in the paper listed as No. 4 in the Bibliography, over a range of frequencies of 200 to 7 000

kilocycles per sec. The results are shown in curve A of Fig. 3 (for R_e) and in Fig. 4 (for X_e). The reactance variation appears to be qualitatively consistent with the generally accepted simple theory, but the second branch appears to have been displaced downwards. This effect was eventually traced to the influence of the earth lead and it was found possible to apply a correction in a manner to be described more fully later on. The corrected reactance/frequency curves for an aerial of length $38{\cdot}6 - 2{\cdot}5 = 36{\cdot}1$ m (i.e. shortened by the length of the earth lead) are given in Fig. 5.

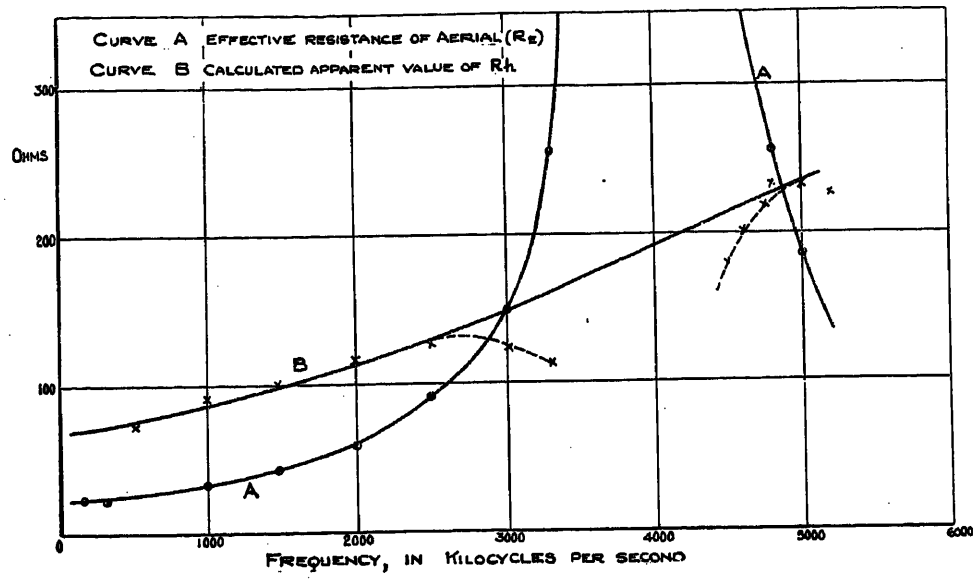


FIG. 3.

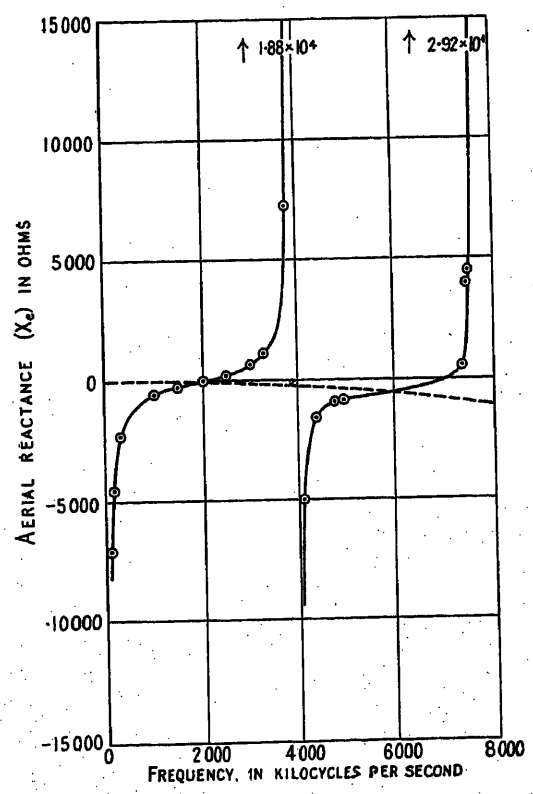


FIG. 4.

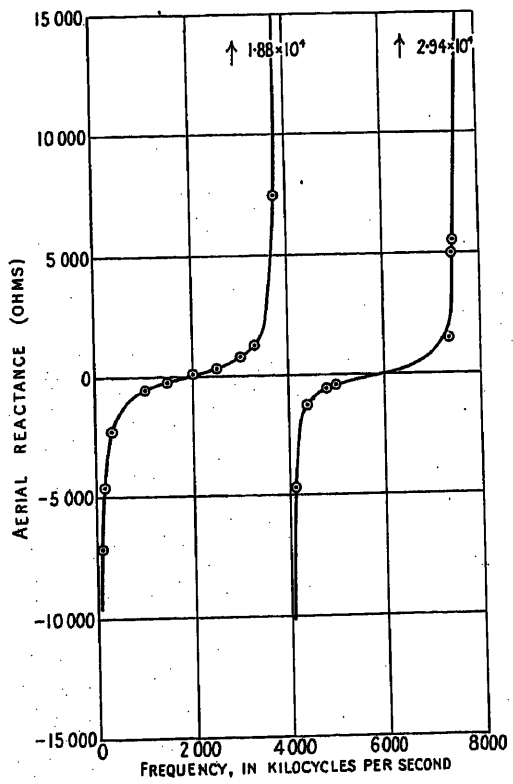


FIG. 5.—Aerial reactance curves corrected for effect of earth lead.

The data represented by curve A of Fig. 3 and the

curve of Fig. 4 will now be compared with the theory given in Section (3).

(5) Quantitative Analysis of the Measured Values of Aerial Impedance.

In order to explain the correction for the earth lead referred to in Section (4) it will be necessary to describe in outline the method of measurement. Referring to Fig. 6, the measurements were made by determining the changes in the apparent constants (resistance and reactance) of the coil $L_1C_1R_1$ when the aerial was connected at the point A, the earth lead being connected all the time. What was actually measured was, therefore, $Z_e + Z_l$ (see Fig. 6*b*), Z_e being the impedance of the aerial alone ($38{\cdot}6 - 2{\cdot}5 = 36{\cdot}1$ m long) and Z_l the impedance of the earth lead as modified by the capacitance to earth of the screening cases of the condensers

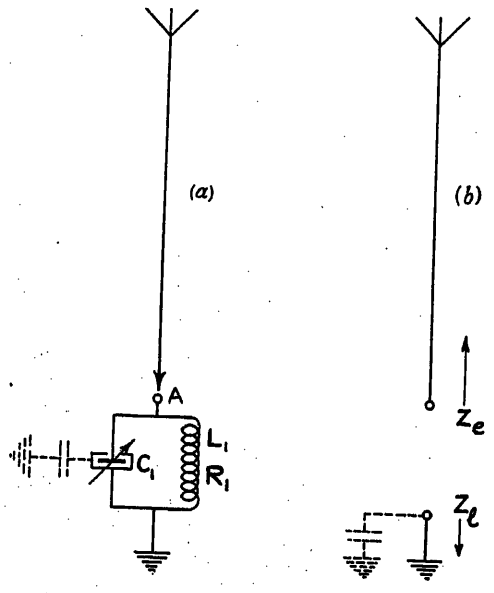


Fig. 6.

employed (shown dotted in Fig. 6*a*). The apparent zero-reactance conditions were therefore those for which the reactance of Z_e was equal and opposite to that of Z_l. Though the impedance of the earth lead alone would not have been very large it was evidently very greatly increased by the parallel capacitance C_e, which was estimated to be of the order of 10^{-11} at least. Unfortunately the very appreciable effect of the earth-lead impedance was not realized until the measurements had been completed, or steps would have been taken for its minimization. However, the measurements having been made, it was decided to allow for the effect by assuming that the displacement of the centre of symmetry of each branch of the reactance curve below the axis gave the magnitude of the reactance of the earth-lead system at the frequency concerned. This gave the origin and two other points through which to draw a line showing the reactance of the earth-lead system as a function of frequency. From this line the necessary correction was found and applied to the apparent reactance to obtain the true reactance of the aerial of length $38{\cdot}6 - 2{\cdot}5$ m. The curve of Fig. 5 was obtained in this way. This process may perhaps be regarded as begging the question as to the cause of the displacement of the reactance curves, but a calculation based on measured and estimated data showed the magnitude of the effect to be quite consistent with the assigned cause. The following comparisons of calculated and measured values are based on Fig. 5, which is taken to represent the variation with frequency of the reactance of an aerial of length $h = 36{\cdot}1$ m.

The observed variation of resistance will first be considered, as resistance terms are involved as corrections in the resonance conditions.

(*a*) *Analysis of the Observed Variation of Aerial Resistance.*

It was shown in Section (2) that, except for frequencies in the immediate neighbourhood of those for which $\cos 2\beta h = 1$, the value of R_e is given by

$$R_e = Rh\frac{2\beta h - \sin 2\beta h}{2\beta h(1 - \cos 2\beta h)}$$

The form of the expression emphasises the fact that R_e depends on two factors—the first being the resistance per unit length multiplied by the total length, and the second a factor expressing the way that the current distribution controls the extent to which the first factor enters into the effective resistance. The first factor is, of course, not a constant with respect to frequency, since it involves radiation resistance, ordinary ohmic resistance, and dielectric and eddy-current losses in the surroundings. It will obviously be of interest to separate these two factors of R_e. Unfortunately β, and therefore the current distribution factor, involves R as a small correction term, as already explained, but as a first approximation this can be neglected. We then have from the curve of Fig. 5 that

$$2\beta h = \pi \text{ when } f = 1\,970 \text{ kilocycles per sec.}$$

and since on the above assumption β is proportional to f

$$2\beta h = \frac{\pi}{1\,970}f$$

Thus βh can be found for any assigned value of f, and the corresponding value of the current distribution factor read from the curves of Fig. 1. Rh can then be found as a function of frequency. The result is shown as curve B in Fig. 3. The dotted deviations from the full-line curve are obviously associated with the region $2\beta h = \pi$, where the approximate formula is no longer valid.

It appears that Rh rises fairly rapidly with frequency. Actually measurements were made at much higher frequencies—up to 10 000 kilocycles or so (30 m)—but subsequent checks on the measuring apparatus revealed a possibility of error in the results and it was thought necessary to discard them. However, allowing for this possibility, it seemed that Rh tended to rise very rapidly at the higher frequencies and might possibly become an appreciable factor in the natural frequencies of the aerial under such conditions.

(*b*) *Additional Measurements of Effective Resistance.*

For wavelengths long compared with the length of the aerial the effective resistance R_e has been shown by analysis to approach the value $R_e = \frac{1}{3}Rh$, where R is the assumed uniform resistance per unit length of the aerial.

The term R is obviously a summation of all the factors which give rise at any point in the aerial to potential differences which are in anti-phase with the current at that point, and therefore includes ohmic resistance, radiation resistance, and dielectric and eddy-current losses in the surroundings of the aerial. Of these the ohmic resistance is the only one which is dependent on the actual material of the aerial, for a given length and configuration. Thus

$$R_e = \frac{R_0 h}{3} + \frac{R_c h}{3}$$

where R_0 is the ohmic resistance per unit length and R_c is a composite effective resistance representing the remaining power-dissipating elements.

To get some idea of the relative magnitude of these terms, measurements were made of the effective resistance of the aerial at about 842 kilocycles per sec. (i.e. λ about 9·4 times h) with conductors of 3/19 S.W.G. enamelled copper, No. 34 tinned copper, and finally No. 47 double-silk-covered copper. The results were as given in Table 1.

The values of $R_0 h$ at the frequency concerned (calculated from the measured d.c. values by applying the appropriate skin-effect correction) are also shown in Table 1. It will be seen that $R_e - R_0 h/3$ is approximately constant, consistent with the above simple analysis.

It appears, therefore, that with the aerial of 3/19 copper the resistance term is almost entirely due to radiation resistance and to eddy-current and dielectric losses in the surroundings of the aerial. Of this the radiation resistance is only a small part. Its value is calculable from the well-known formulæ, and would only be about 0·5 ohm. Thus practically the whole of the aerial resistance in the case under consideration is due to purely parasitic eddy-current and dielectric losses.

T. L. Eckersley* has shown how these losses can be minimized by the use of a screen of high-conductivity wires shielding the ground in the immediate neighbourhood of the aerial from the relatively concentrated electric fields in that region. His work was concerned with transmitting aerials but is equally applicable to receiving aerials. With a view to confirming the assumption as to the nature of the losses represented by the resistance of the aerial, the buried copper-plate earthing system was replaced by a single insulated wire running parallel to and underneath the horizontal part of the aerial at a height of about 1 m above the ground. The effective resistance was measured and found to have been reduced from 30 ohms to 9 ohms by this rudimentary form of screen. With the same wire lowered on to the surface of the ground the effective resistance increased to 108 ohms. With a small earthing pin the effective resistance was 150 ohms. All these results are consistent with the view that the resistance of an earthed aerial can only be minimized by avoiding, as far as possible, any concentration of electric field in the earth in the neighbourhood of the aerial.

It is not possible to make a detailed comparison of the observed and calculated variation of R_e with frequency, since the necessary data are not available. There is some slight evidential value in Table 1, but a more satisfactory comparison of theory and observation can be obtained by an analysis of the reactance curves, the necessary correcting factors due to resistance being determined from the observed resistance variation.

TABLE 1.

Aerial	R_e	R_0h (d.c.)	R_0h (a.c.)	$R_e - (R_0h/3)$
3/19 S.W.G. enamelled copper	30	0·35	2·45	29·2
No. 34 tinned copper	33·8	15·8	17·4	28·0
No. 47 d.s.c. copper	138·5	329	329	28·8

(*c*) *Analysis of Observed Variations of Aerial Reactance.*

The resistance measurements are considered quite reliable up to about 5 000 kilocycles per sec., and the data obtained can be used for determining the effect of resistance on the critical reactance conditions corresponding to the lower natural frequencies of the aerial.

The value of ah is derived from the value of Rh and Ch as follows. From the definition of α and β

$$2\alpha\beta = \omega CR \quad . \quad . \quad . \quad . \quad . \quad (31)$$

From this can be derived

$$ah = \frac{3 \times 10^{10}}{2h} Ch \,.\, Rh \quad . \quad . \quad . \quad (32)$$

The value of Ch (see below) is very approximately 230 $\mu\mu$F, and, from the curves of Fig. 3, Rh is 110 at 1 970 kilocycles per sec.

Therefore $$ah = 0{\cdot}105$$

Referring to equation (23), the correction term involved in the resonance relations between λ and h is, for the fundamental resonance ($n = 1$), $2(ah)^2/\pi^2$. The value of this is 0·0022. Thus, so far as the critical reactance conditions are concerned, the resistance correction can be neglected to an accuracy of about 2 parts in 1 000. The correction will probably decrease with the order of the harmonic concerned, since n^2 appears in the denominator, but since $(ah)^2$ appears in the numerator and a

* See Bibliography, (5).

increases fairly rapidly with n (i.e. with the frequency), it is not necessarily safe to assume that it is negligible at very high frequencies. This is a matter requiring further investigation. Up to $n = 3$ or 4, however, it is clear that we can use the simple relationship

$$\lambda = \frac{4h}{n} \qquad n = 1, 2, 3 \quad . \quad . \quad . \quad (33)$$

for the comparison of measured and calculated resonance conditions. The comparison is given in Table 2 in the form of observed and calculated values of λ, assuming h to be 36·1 metres.

The most striking feature of the results is that the difference between the observed and calculated values is about 5 per cent throughout. If the length were assumed to be 36·1 + 5 per cent, i.e. 36·1 + 1·8 = 38 m, the observed and calculated values would be in agreement to about 1 per cent, which is about the probable accuracy of measurement. Thus the assumptions on which the analysis is based would appear to be valid to 1 per cent

TABLE 2.

n	λ (obs.)	λ (calc.)	f (obs.)	f (calc.)	Percentage difference
	metres	metres	kilocycles/sec.	kilocycles/sec.	
1	152·4	144·4	1 970	2 080	5·2
2	76·0	72·2	3 950	4 160	5
3	50·3	48·1	5 970	6 240	4·2
4	38·5	36·1	7 800	8 310	6·2

or so, provided the actual length of the aerial be increased by 1·8 m, i.e. the resonances are given by

$$\lambda = \frac{4}{n}(h + \epsilon) \quad . \quad . \quad . \quad . \quad . \quad (34)$$

ϵ being the above small correction term, presumably attributable to end-effect. This is analogous to the similar correction applied to the open organ pipe (i.e. + 0·58 × radius of pipe).

Wilmotte* found the result $\lambda = 4 \cdot 2h$ for a transmitting antenna 11 m high, the conductor being of cage form about 11 cm in diameter. He also states in the paper referred to that Abraham and Föppl arrived at the figure 4·2 by a more rigid analysis than that given in this paper. The results of the present measurements are in very satisfactory agreement with Wilmotte's measurements and Abraham and Föppl's calculation, for they give

$$\lambda = 4 \cdot 22h$$

(From the agreement between the present measurements and Wilmotte's result it would appear that the end correction is not critically dependent on the ratio of length to diameter of the aerial conductor.)

Certain other points on the reactance curves lend themselves to quantitative comparison of the theoretical and observed behaviour, namely those for which $2\beta h = (2n + 1)\pi/2$. As shown in Section 3(*b*), the corresponding reactances are $\pm 1/C \times 3 \times 10^{10}$. In addition, when $\beta h \to 0$, the reactance tends to $-1/\omega Ch$.

* See Bibliography, (11).

From reactance curves drawn to a large scale and corrected as already explained for the reactance of the earth lead, it was found that the reactances for these points with $n = 0$ and $n = 1$ (i.e. $\lambda = 8h$ and $8h/3$) were − 550 and + 530 ohms respectively, giving C as 0·061 and 0·063 $\mu\mu$F. The corresponding values of Ch (taking h as the corrected value 38 m) are 230 and 239 $\mu\mu$F. At low frequencies Ch is found from the curve to approach the limiting value 227 $\mu\mu$F. The experimental curves are thus self-consistent to this degree.

The general conclusion is that the analysis gives a satisfactory account of the behaviour of the aerial impedance as a function of aerial length and of frequency, provided the actual length be replaced by the slightly increased effective length (i.e. $h + 0 \cdot 05h$) as already explained.

The analysis and the fundamental assumptions having been confirmed to this degree by experiment, we can now proceed with a certain assurance to the further examination of the subject, with a view to obtaining the maximum amount of information by purely analytical methods.

Part 2.

(6) Further Analysis of the Behaviour of a Receiving Aerial as Deduced from the Transmission-Line Equations.

The work already described has established the fact that the classical transmission-line equations, with the assumption of uniform distributed constants, can be applied to the case of a receiving aerial, and that the results so deduced will be in agreement with observation to an approximation sufficiently close to be practically useful. In this second part of the paper, therefore, the purely analytical examination is continued, and information is obtained on the following points:—

(*a*) The magnitude of the e.m.f. induced in a plain aerial in a non-uniform field.
(*b*) The nature of the variation of the induced e.m.f. with aerial height and with frequency.
(*c*) The efficiency of an aerial as a collector of electrical energy from an electric field.
(*d*) The difference between the current distribution in receiving and transmitting aerials.

It happens that for the above purposes it is necessary to consider the case illustrated in Fig. 7, i.e. an aerial assumed to have uniform distributed constants, but divided into three distinct parts, of lengths h_1, h_2, and h_3, as far as the inducing electric field is concerned. In each part it is assumed that a uniform electric field of intensities e_1, e_2, e_3, and of pulsatance ω, acts along the respective parts of the aerial. The analysis of this case is naturally somewhat laborious, but does not differ in any essential respect from that of the simpler case and need not therefore be given in detail.

It is found that the current at the base of the aerial can be expressed in the form

$$i_0 = \frac{e_{e1} + e_{e2} + e_{e3}}{Z_e} \quad . \quad . \quad . \quad . \quad (35)$$

where e_{e1}, e_{e2}, and e_{e3} are elements of effective e.m.f. due to the assumed intensities e_1, e_2, and e_3 respectively. The full expressions for these three effective e.m.f.'s are as follows:—

$$e_{e1} = \frac{\cosh Ph - \cosh P(h_2 + h_3)}{\sinh Ph} \cdot \frac{e_1}{P} \quad . \quad . \quad (36)$$

$$e_{e2} = \frac{\cosh P(h_2 + h_3) - \cosh Ph_3}{\sinh Ph} \cdot \frac{e_2}{P} \quad . \quad . \quad (37)$$

$$e_{e3} = \frac{\cosh Ph_3 - 1}{\sinh Ph} \cdot \frac{e_3}{P} \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

where P has the significance already defined. It is

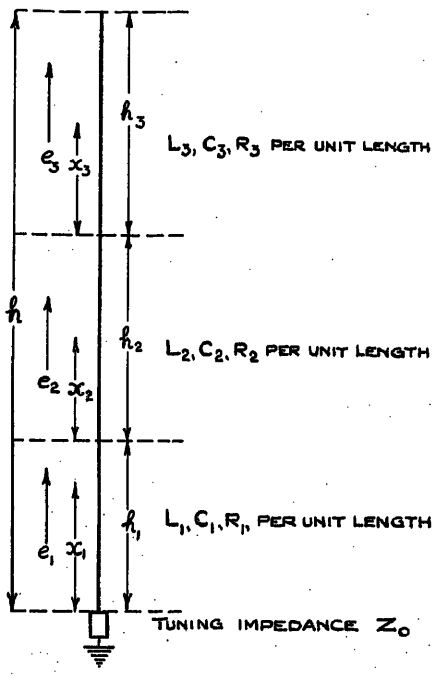


FIG. 7.

important to note that the effective impedance associated with each element of the e.m.f. is the same, i.e. Z_e or $Z \coth Ph$.

The above configuration may seem somewhat artificial and elaborate, but its justification lies in the facility with which important practical cases can be derived as special cases of the general formulæ.

(7) DEDUCTION OF A LINE INTEGRAL FORMULA FOR THE E.M.F. INDUCED IN A PLAIN AERIAL IN ANY GIVEN NON-UNIFORM FIELD.

Consider first the special case, illustrated in Fig. 8(*a*), where $e_1 = e_3 = 0$ and $e_2 = e$. This is not, of course, a practical case but is a purely analytical manipulation for the purpose stated in the heading. Then

$$e_e = \frac{\cosh P(h_2 + h_3) - \cosh Ph_3}{\sinh Ph} \cdot \frac{e}{P} \quad . \quad . \quad . \quad (39)$$

By a familiar transformation this can be put in the form

$$e_e = \frac{2 \sinh P(h - h_1 - h_2/2) \sinh Ph_2/2}{\sinh Ph} \cdot \frac{e}{P} \quad . \quad (40)$$

Now let h_2 be reduced to the ultimately vanishing element dx, and put $h_1 = x$, as shown in Fig. 8(*b*). Writing de_e for the resultant element of effective e.m.f. we have

$$de_e = \frac{2 \sinh P(h - x - dx/2) \sinh Pdx/2}{\sinh Ph} \cdot \frac{e}{P}$$

Now the limit of $(2/P) \sinh (Pdx/2)$ when $dx \to 0$ is dx. Therefore in the limit we have

$$de_e = \frac{e \sinh P(h - x)dx}{\sinh Ph} \quad . \quad . \quad . \quad (41)$$

If we now assume e to be a function of x (both as to amplitude and phase in general), and write it $e(x)$ to emphasize this functional character, then $e(x)dx$ is the

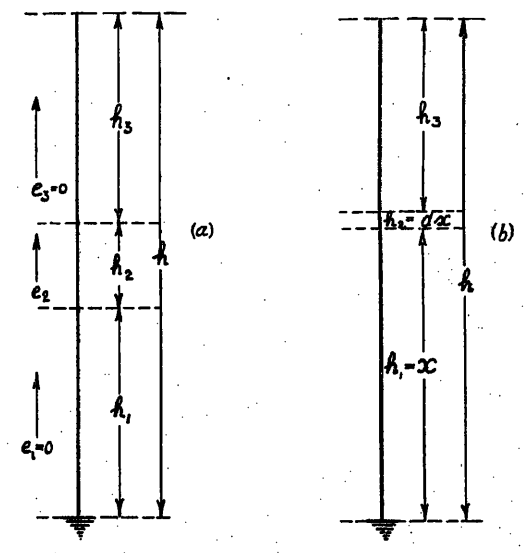


FIG. 8.

component of the field along the aerial at the point x. Since as far as the current at the base of the aerial is concerned the effective impedance associated with each element of e.m.f. is the same, the total effective e.m.f. can be obtained by the summation or integration (in the vector sense, of course) of all the elements of e.m.f., and is given by

$$e_e = \frac{1}{\sinh Ph} \int_0^h e(x) \sinh P(h - x)dx \quad . \quad . \quad (42)$$

This formula was obtained in a less intelligible operational form in the original paper by the present author.* R. M. Wilmotte has also derived and published a similar line integral formula† though it appears in a somewhat different form, the resistance component of P being omitted and the sign of the e.m.f. reversed. (This would appear to be an error, since some experimental work by

* See Bibliography, (1). † *Ibid.*, (7).

the Post Office, referred to more fully below, was found to be in agreement with the formula as stated above.) Actually the effect of the resistance term in P is likely, in general, to be negligible and the integral can be simplified somewhat to

$$e_e = \frac{1}{\sin \beta h}\int_0^h e(x) \sin \beta(h-x)dx \quad . \quad . \quad . \quad (43)$$

$$= \frac{1}{\sin 2\pi h/\lambda}\int_0^h e(x) \sin \frac{2\pi}{\lambda}(h-x)dx \quad . \quad . \quad (44)$$

but this formula cannot be applied when $h = n\lambda$, as the first factor becomes infinite. For such cases the more exact form is required. It should be borne in mind that this formula refers to the value of e due to the transmitting system when the receiving system is present. In certain cases, e.g. aerial and reflector systems, the current in the transmitting system, and therefore the field due to it, will be modified by the presence of the receiving (or reflecting) system. The formula will, however, still be applicable. It has, in fact, already been applied to such a system by the Post Office Engineering Department; it gave results consistent with actual measurement.

The evaluation of $e(x)$ in such cases can be arrived at by a method such as McPetrie's,* provided the current distribution as modified by the presence of the reflecting system be used as the basis for the calculation. This determination, though not rigid, appears to be sufficiently accurate for practical purposes, and is simpler than the more exact formulation of the problem given by Bechmann.† Bechmann's work on this subject is, however, of major importance and is likely to have very great practical value.

It should be noted as a special case that if e be assumed uniform we arrive at

$$e_e = \frac{e}{\sinh Ph}\int_0^h \sinh P(h-x)dx \quad . \quad . \quad (45)$$

$$= \frac{\cosh Ph - 1}{\sinh Ph}\cdot\frac{e}{P} \quad . \quad . \quad . \quad . \quad . \quad (46)$$

which is in agreement with previous results.

(8) General Character of the Variation of Effective E.M.F. with Frequency.

To obtain first some general idea of the variation of the effective e.m.f. with frequency it will be well to consider the simplest case, e.g. a plain aerial of height h in a uniform field. The corresponding formulæ are

$$e_e = \frac{e}{P}\cdot\frac{\cosh Ph - 1}{\sinh Ph} = \frac{e}{P}\tanh\frac{Ph}{2} \quad . \quad (47)$$

and $$Z_e = Z \coth Ph$$

If as a first approximation we neglect α altogether

$$e_e = \frac{1}{\beta}\tan\frac{\beta h}{2}e = \frac{\lambda}{2\pi}\tan\frac{\pi h}{\lambda}e \quad . \quad . \quad . \quad (48)$$

* See Bibliography, (9). † *Ibid.*, (8).

The limiting value when $\beta h \to 0$, i.e. when h is very short compared with λ, is $\frac{1}{2}he$—corresponding to the well-known result that the "effective height" is half the actual height under such conditions. The variation of e_e with frequency with the resistance neglected is of the form

$$e_e = \frac{\lambda}{\pi h}\tan\frac{\pi h}{\lambda}\cdot\frac{he}{2} = \frac{1}{\theta}\tan\theta\cdot\frac{he}{2} \quad . \quad . \quad (49)$$

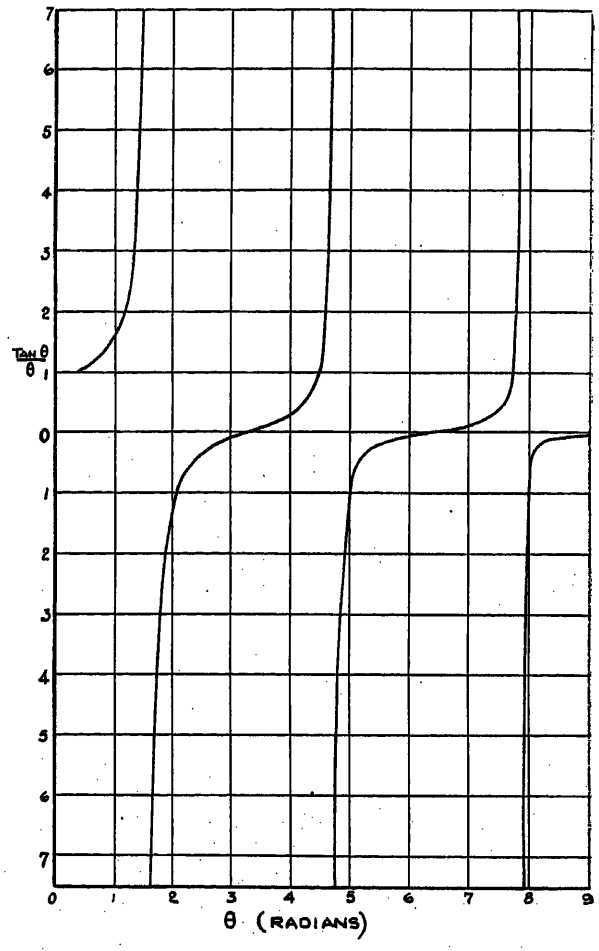


Fig. 9.

where θ is written for $\pi h/\lambda$. The function $\tan\theta/\theta$ is illustrated in Fig. 9.

One important practical conclusion is already obvious. For a given wavelength the variation of e_e with h is, apart from any effect of resistance terms, periodic with constant amplitude. In other words, if

$$\frac{\pi h}{\lambda} = n\pi + \phi$$

$$e_e = \left(\frac{\lambda}{2\pi}\tan\phi\right)e$$

i.e. e_e does not increase with n. Thus for a given value of ϕ an aerial several wavelengths high is no better than the shortest aerial which will give the same value of ϕ,

unless, of course, means are adopted for suppressing the undesired half wavelengths as in the case of the well-known construction introduced by Franklin.

For a more detailed examination of the critical values of the effective e.m.f. it is necessary to take the resistance terms into account. The exact formula is

$$|e_e| = \frac{e_{max.}}{\sqrt{[a^2+\beta^2]}} \cdot \frac{\sqrt{[\sinh^2 ah + \sin^2 \beta h]}}{\cosh ah + \cos \beta h} \quad . \quad (50)$$

The function does not vary steeply in the regions corresponding to the $(2n+1)\lambda/4$ resonances, and for these points the approximation

$$\beta h = (2n+1)\pi/2$$

may be safely used. For such values of βh

$$|e_e| = \frac{e_{max.}}{\sqrt{[a^2+\beta^2]}} \quad . \quad . \quad . \quad . \quad (51)$$

Now as $a/\beta = R/(2L)$, $a^2/(2\beta^2)$ will be negligible compared with 1 in all ordinary cases, so that when $h = (2n+1)\lambda/4$,

$$|e_e| = \frac{e_{max.}}{\beta} = \frac{\lambda e_{max.}}{2\pi} = \frac{2}{(2n+1)\pi} h e_{max.} \quad . \quad (52)$$

confirming the fact already noted, that for a given wavelength $|e_e|$ does not increase with n.

In the neighbourhood of the resonances corresponding to $h = (2n+1)\lambda/2$, e_e obviously becomes very large. In fact when $h = (2n+1)\lambda/2$, i.e. $\beta h = (2n+1)\pi$,

$$|e_e| = \frac{e_{max.}}{\sqrt{[a^2+\beta^2]}} \coth \frac{ah}{2} \quad . \quad . \quad . \quad (53)$$

but owing to the steepness of the variation with frequency in these regions the exact value of the resonant frequency would have to be used in determining $|e_e|$ at resonance, leading to a complicated expression which does not permit of approximation.

For $h = n\lambda$ (i.e. $\beta h = 2n\pi$), $|e_e|$ is very small, being given by

$$|e_e| = \frac{e_{max.}}{\sqrt{[a^2+\beta^2]}} \tanh \frac{ah}{2} \quad . \quad . \quad . \quad (54)$$

(9) Relative Effectiveness of Different Parts of a Receiving Aerial.

The formulæ for the contribution of each element of the system considered in Section (6) to the total effective e.m.f. at the base of the aerial afford interesting information as to the relative effectiveness of successive elements of the length of a plain receiving aerial from this point of view.

If the total height of the aerial be small compared with the wavelength of operation, the resistance terms in the formulæ can safely be neglected and they take the simple form

$$e_{e1} = k\{\cos \beta(h_2 + h_3) - \cos \beta h\} \quad . \quad . \quad (55)$$
$$e_{e2} = k\{\cos \beta h_3 - \cos \beta(h_2 + h_3)\}$$
$$e_{e3} = k\{1 - \cos \beta h_3\}$$

where $k = je/\beta \sin \beta h$

e being the intensity of the field, assumed uniform with respect to h.

Suppose, for example, that $\beta h = 0{\cdot}3\pi$ or $h = 0{\cdot}15\lambda$, and that $h_1 = h_2 = h_3 = h/3$. Then

$$|e_{e1}| = k(\cos 36° - \cos 54°) = 0{\cdot}221k$$
$$|e_{e2}| = k(\cos 18° - \cos 36°) = 0{\cdot}142k$$
$$|e_{e3}| = k(1 - \cos 18°) = 0{\cdot}05k$$

showing that the contribution of the top third of the aerial is less than a quarter of that of the bottom third. Thus the most important effect of the upper elements of the aerial is to increase the effectiveness of the lower parts rather than to make their own direct contribution to the effective e.m.f. This fact can be illustrated further by considering the two systems illustrated in Fig. 10. These are assumed to be excited by a wave travelling normal to the plane of the paper. It might be thought that since the e.m.f. induced in the far downward element C_2D_2 in the second system is opposed to that induced in the earthed vertical element C_1D_1, the resultant e.m.f. induced in the whole system would be very small. Actually, the additional length in the second system

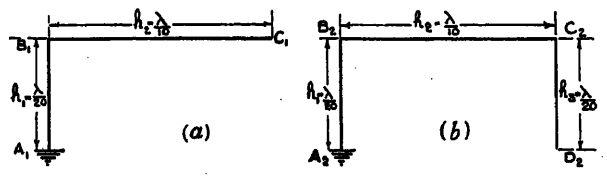


Fig. 10.

represented by the downward element C_2D_2 so much increases the effectiveness of the upward vertical element that the total resultant e.m.f. is not decreased but is even greater by a small amount than that given by the first system. For the first system

$$|e_e| = k\{\cos 36° - \cos 54°\} = 0{\cdot}221k$$

and for the second

$$|e_e| = k\{(\cos 54° - \cos 72°) - (1 - \cos 18°)\}$$
$$= k\{0{\cdot}279 - 0{\cdot}049\}$$
$$= 0{\cdot}230k$$

It must be remembered, however, that the resistance of the second system is higher than that of the first, so that whether in practice a larger received current would be obtainable from the second system than from the first would depend on other circuit conditions. If, however, the function of the system be to provide e.m.f. rather than power, a gain of 5 per cent is obtained at no additional cost for masts. The increase would, of course, be even greater for a wave travelling in the direction of the horizontal element, for the phase difference between e_3 and e_1 would then be less than 180°. However, the case is put forward for the sake of the interest of the somewhat paradoxical result obtained, rather than as a practical suggestion.

(10) A Simple Directive Receiving System.

The conclusions of the preceding Section do not, of course, apply to cases where the aerial is not short compared with the wavelength. Consider, for example, the system illustrated in Fig. 11. For a vertically polarized wave travelling normal to the plane of the paper $e_1 = -e_3 = e$, and $e_2 = 0$. Omitting for the present the resistance terms from the e.m.f. formulæ, we have

$$e_{e1} = k\left\{\cos\frac{3\pi}{2} - \cos 2\pi\right\} = -k$$

and

$$e_{e3} = -k\left\{1 - \cos\frac{\pi}{2}\right\} = -k$$

where k is written for $je/(\beta \sin 2\pi)$ (apparently infinite, but limited by the resistance terms of the exact formula). Thus for a wave in the specified direction

$$e_e = e_{e1} + e_{e3} = -2k$$

If, however, the wave arrives in the direction of the horizontal half-wave element of the aerial, then, owing

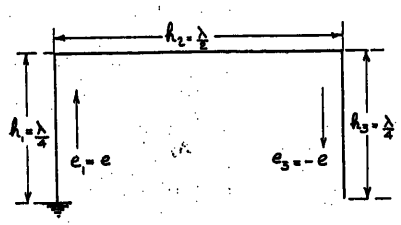


Fig. 11.

to the phase difference of the fields at the two vertical elements,

$$e_1 = e_3 = e$$

so that

$$e_e = e_{e1} + e_{e3} = -k + k = 0$$

Such an aerial system will, therefore, have a polar diagram of figure-of-eight type for its receptivity similar to that of a frame aerial but with a different law. Neglecting resistance terms, the law will be $\cos(\frac{1}{2}\pi \cos\theta)$, θ being the angle between the plane of the aerial and the vertical plane containing the direction of the wave. It is, of course, similar in principle to the free-ended half-wave systems commonly employed in beam transmitting systems.

The simple theory given above is, of course, modified somewhat when the exact formulæ are used. It may be pointed out that the difference between the approximate and exact formulæ may be greater than is commonly assumed, and that the effect of the resistance terms may introduce quite appreciable differences between the simply calculated and the actual behaviour. From the measurements described in Section (4), for example, it appears that the value of ah_1, when h is $\lambda/4$, is about 0·1, so that in the system described above ah might easily have a value of 0·4 or more, giving cosh ah about 1·08 instead of 1 as assumed in the simple theory. In addition there is the fact already mentioned in the discussion of the measured values, namely, that the effective length of the aerial may be 5 per cent or so longer than the actual length.

These possible discrepancies between the simple theory and observed behaviour are likely to be greater at higher frequencies. In this matter there is a need for more information than is at present available.

(11) The Principle of the Suppressed Half Wavelength Aerial.

The principle of the suppressed half wavelength aerial, developed by Franklin, is made very clear as far as reception is concerned by means of the effective e.m.f.

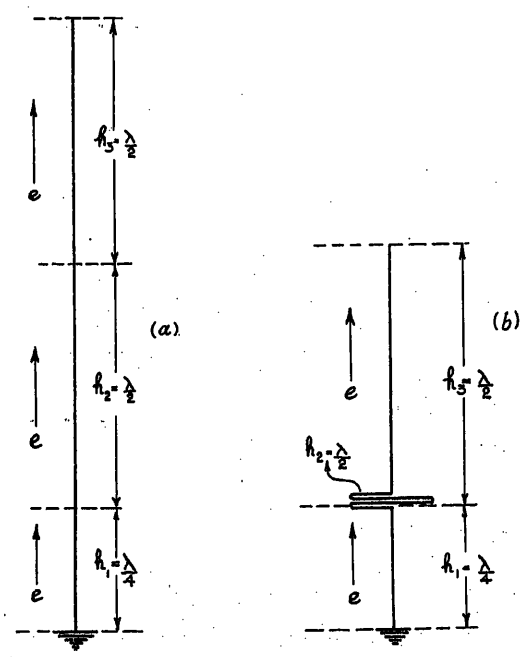


Fig. 12.

formulæ. Consider the system illustrated in Fig. 12(*a*), the aerial being assumed to be excited by a uniform field. Using the same symbols as in Section (9) and omitting the resistance terms for sake of simplicity of explanation

$$e_{e1} = k(\cos 2\pi - \cos 5\pi/2) = k$$
$$e_{e2} = k(\cos\pi - \cos 2\pi) = -2k$$
$$e_{e3} = k(1 - \cos\pi) = 2k$$

Therefore $e_e = e_{e1} + e_{e2} + e_{e3} = k$

which is the same value as would be obtained by h_1 alone (i.e. the first quarter wavelength element), but associated with a higher aerial resistance and therefore very much less effective as a source of power. If, however, the field be prevented from acting on the element h_2 [by a suitable disposition of the wire, as in Fig. 12(*b*)], then $e_{e2} = 0$ and $e_e = e_{e1} + e_{e3} = 3k$.

As already pointed out, the actual behaviour may be appreciably modified by the effect of the resistance terms

in a manner easily determinable from the exact formulæ (assuming the necessary data to be available), but the principle will be the same.

The power aspect of the matter will be referred to again in the following Section.

(12) The "Effective Height" of a Receiving Aerial.

In the case of a receiving aerial system in which the vertical part, of height h, is parallel to a uniform field of intensity e, the aerial can be said to have an effective height h_e defined by the relation

$$|e_e| = |e|\,h_e \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

This is a generalized definition of effective height for reception which is consistent with the accepted usage of that term. For example, if the aerial is a plain vertical aerial in a uniform vertically polarized field

$$e_e = \frac{e}{P}\tanh\frac{Ph}{2}$$

and if Ph is small (i.e. if h is small compared with λ) $\tanh Ph/2$ is very approximately equal to $Ph/2$, so that

$$e_e = \frac{e}{P}\cdot\frac{Ph}{2} = e\frac{h}{2}$$

and

$$h_e = \frac{h}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

The conception of "effective height" is, however, of very doubtful utility. In the first place it is misleading in so far as it implies that the "effective height" of an aerial is a quantity characteristic of the given aerial structure concerned and thus useful as a criterion of its effectiveness for reception. In actual fact it is a quantity dependent on the wavelength of operation, the configuration of the field and, in many cases, on the direction of the wave in relation to the configuration of the aerial. Only in the very special case of a non-directional receiving system the effective elements of which are assumed to be parallel to a uniform field has the conception any very clear physical significance, and even in this case it is a function of frequency unless the latter is assumed to be low compared with the natural frequency of the aerial.

It would, of course, be a convenience if an aerial structure could be characterized by some constant which was useful as a criterion of its effectiveness in relation to its intended function, but the number of variables involved in practice makes any complete generalization on these lines impossible. In general nothing short of a complete geometrical and physical description of the structure will give the information required for the determination of its behaviour in response to assigned conditions of excitation, and any description in terms of some single quantity such as "effective height" is likely to achieve a deceptive simplicity at the expense of exactness.

There is, however, no need to labour this point, as the term, whether in relation to reception or transmission (when similar criticisms apply) is now much less frequently used than was formerly the case. It was a term appropriate to the early days of the development of the science and art of radio communication, but it has now to a large extent outlived its usefulness.

(13) A Receiving Aerial Considered as a Collector of Power.

It is perhaps an arguable question whether the valve receiving systems of the present day should be regarded as power or potential-operated devices. In practice the actual requirements and consequently the circuit conditions will vary considerably, so that sometimes the one and sometimes the other point of view will be appropriate. There certainly are many cases where the function of the receiving aerial should be considered as the absorption of power from the field. In relation to all such cases the representation of the received current at the base of the aerial in the form

$$i = \frac{e_e}{Z_e + Z_0}$$

where Z_0 is the impedance of the tuning circuit (including of course the input impedance of the detecting or receiving apparatus), has the important advantage of depicting the system as a source of power. It is well known that the maximum power available for utilization in such a system is given by*

$$W_{max.} = \frac{1}{4}\cdot\frac{E_e^2}{R_e}$$

where E_e is the R.M.S. value of e_e. Thus E_e^2/R_e or $|e_e|^2/R_e$ is the appropriate figure of merit for the system considered as a collector of power from the field and as a source of power for the operation of the receiving system.

The formulæ already developed enable this factor to be expressed in terms of the constants of the aerial and the configuration and intensity of the field. For the simple case of a plain vertical aerial in a uniform field of intensity $e_{max.}$ volts per cm the formula becomes

$$\frac{|e_e|^2}{R_e} = \frac{\alpha\beta}{\alpha^2+\beta^2}\cdot\frac{(\cosh 2\alpha h - \cos 2\beta h)^2}{(\cosh\alpha h + \cos\beta h)^2(\beta\sinh 2\alpha h - \alpha\sin 2\beta h)}\cdot\frac{e_{max.}}{R} \quad . \quad . \quad . \quad . \quad (58)$$

or, since

$$(\cosh^2\alpha h - \cos^2\beta h) = (\sinh^2\alpha h + \sin^2\beta h) = \tfrac{1}{2}(\cosh 2\alpha h - \cos 2\beta)$$

is very approximately

$$\frac{|e_e|^2}{R_e} = \frac{\{(1-\cos\beta h) + \alpha^2h^2/2\}^2}{(2\beta h - \sin 2\beta h)}\cdot\frac{4}{\beta}\cdot\frac{e_{max.}^2}{R} \quad . \quad (59)$$

The general character of this function is fairly clear. It will reach a maximum value in the region of $\beta h = \pi/2 (h = \lambda/4)$, after which it will oscillate about a

* See Bibliography, (12).

decreasing positive mean value with a decreasing amplitude.

For $h = (2n + 1)\lambda/4$

$$\frac{|e_e|^2}{R_e} = \frac{2\lambda}{(2n + 1)\pi^2}(ah \coth ah)\frac{e^2_{max.}}{R} \quad . \quad (60)$$

The quantity $(ah \coth ah)$ will not differ greatly from 1 as long as ah is small, so that for a given wavelength the available energy decreases as the number of quarter wavelengths in the height of the aerial.

For $h = (2n + 1)\lambda/2$ and $n\lambda$, $|e_e|^2/R_e$ is very small and decreases with the value of n in a similar manner.

The variation of $|e_e|^2/R_e$ as a function of h is illustrated in Fig. 13, for the values 0 to 4π of βh, assuming $\alpha/\beta = 1/5\pi$ (making it a case comparable with the experimental aerial). It reaches a maximum in the immediate neighbourhood of $h = \lambda/4$ ($\beta h = \pi/2$), and thereafter oscillates with rapidly diminishing amplitude.

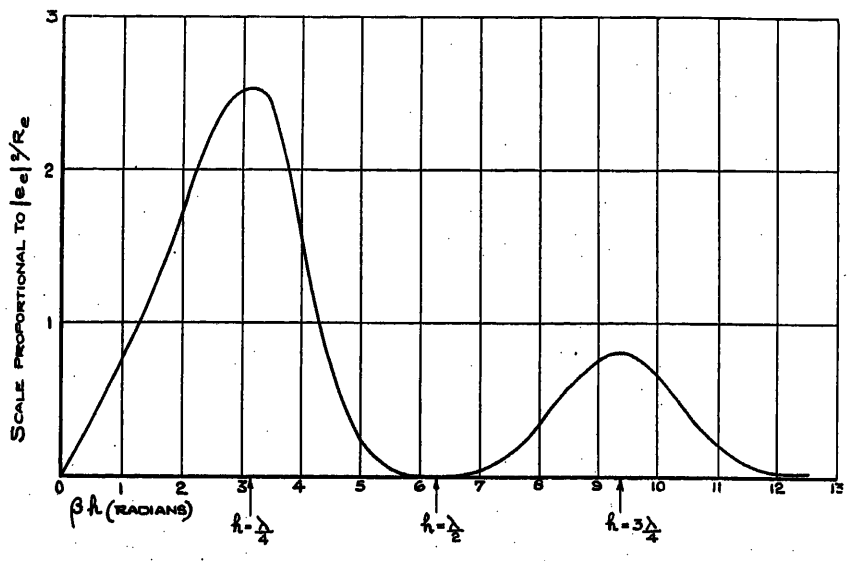


FIG. 13.

The above conclusions as to the undesirability of using aerials of multiples of a quarter wavelength in height (impracticable in any case except at short wavelengths) do not, of course, apply to systems where parts of the height are virtually out of the action of the field, as in the Franklin construction. It has been shown in the preceding Section that with such a construction the effective e.m.f. for $h = 5\lambda/4$ would be three times that for $h = \lambda/4$. It should be borne in mind, however, that the resistance in the former case may be expected to be greater than that in the latter. The gain in available power will only be as 3 : 1 if it be assumed that the resistance of the compressed element is negligible. The radiation resistance of the compressed element is certainly eliminated, but this is not necessarily the major part of its total resistance. If the radiation resistance is small compared with the total resistance, the power gain will only be as 9 : 5. The actual gain will presumably be somewhere between these limits, and will thus in general be less than the ratio of the heights of the two structures. The matter is one on which more experimental data are required.

(14) CURRENT DISTRIBUTION IN TRANSMITTING AND RECEIVING AERIALS.

The analysis has up to this point been mainly concerned with the magnitude of the current at the base of a receiving aerial as a function of the aerial constants and the field. By the same methods, however, an important result relating to current distribution in transmitting and receiving aerials can be demonstrated —namely, the fact that for a given aerial and a given frequency of operation the current distributions may be quite different in the two cases, i.e. reception and transmission. It is commonly assumed that for a given aerial height or length and a given frequency of sinusoidal excitation the current distribution is in the form of a sine wave with the aerial as axis, successive nodes being half a wavelength apart. It appears that this is not generally true. In the case of uniform excitation, for example (a plain vertical receiving aerial in a uniform field), successive current nodes may be separated by any distance from 0 to λ.

This interesting result was apparently first demonstrated by von Korshenewsky* by a simple physical and analytical argument, which was, however, confined to an isolated conductor wire in free space. After reading this paper the present author realized the probable applicability of similar reasoning to the more familiar earthed transmitting and receiving systems, and found that similar conclusions could, in fact, be demonstrated.

The system illustrated in Fig. 14 will serve for both cases under consideration, i.e. transmission and reception. The aerial constants are assumed uniform and the same in both parts $(h_1 + h_2)$. A uniform field (e volts per cm) is assumed to act on the part h_1 only. From

* See Bibliography, (10).

the equations already given, it is a simple matter to derive the formulæ for the currents i_1 and i_2 in the two parts h_1 and h_2 of the aerial, and the current-distribution formulæ for a plain aerial under conditions of reception and transmission respectively can be obtained respectively by making $h_2 = 0$ for the first case and taking the limit when $h_1 \to 0$ with the condition $h_1 e \to e_0$ for the second. This latter process enables us to arrive at the condition somewhat loosely described as a point source of e.m.f. by a continuous variation not involving any discontinuities.

The resistance terms cannot be entirely neglected in the above analysis, because, although the form of the current distribution is practically unaffected by them, they nevertheless determine the maximum amplitudes and their omission would therefore make impossible a

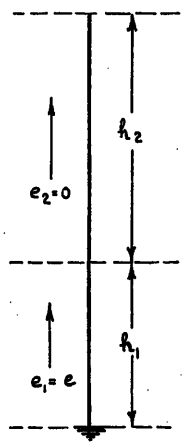


FIG. 14.

full quantitative comparison of the two cases. In each case it is assumed that the aerial is connected to earth through a negligible impedance (i.e. $Z_0 = 0$).

The analysis need not be detailed as it is quite straightforward. The results obtained are

$$i = \frac{2e}{PZ \cosh Ph} \sinh \frac{P(h+x)}{2} \sinh \frac{P(h-x)}{2} \quad . \quad (61)$$

and

$$i = \frac{e_0}{Z \cosh Ph} \sinh P(h-x) \quad . \quad . \quad (62)$$

for reception and transmission respectively. For the actual distributions, apart from resonance conditions, the formulæ in which resistance terms are neglected can be used, and are, of course, somewhat simpler. They are:—

$$i_{max.} = \frac{e_{max.}}{\omega L}\left(1 - \frac{\cos 2\pi x/\lambda}{\cos 2\pi h/\lambda}\right) \text{ for reception} \quad . \quad (63)$$

and

$$i_{max.} = \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L} \cdot \frac{1}{\cos 2\pi h/\lambda} \sin \frac{2\pi}{\lambda}(h-x)$$
$$\text{for transmission} \quad . \quad (64)$$

Note that $i_{max.} = 0$ when $x = h$ in all cases. The omission of the resistance terms clearly leads to infinite values for $i_{max.}$ at resonance conditions for which $\cos 2\pi h/\lambda = 0$, and for all such cases it is essential to apply the exact formulæ for the comparison of the current maxima. The results obtained are:—

h	x	$i_{max.}$
		Reception.
$\frac{1}{4}\lambda$	0	$\coth ah \frac{e_{max.}}{\omega L} \simeq \frac{1}{ah} \cdot \frac{e_{max.}}{\omega L}$
$\frac{1}{2}\lambda$	0	$\frac{1+\cosh ah}{\cosh ah} \cdot \frac{e_{max.}}{\omega L} \simeq \frac{2e_{max.}}{\omega L}$
$\frac{3}{4}\lambda$	0	$\coth ah \frac{e_{max.}}{\omega L} \simeq \frac{1}{ah} \cdot \frac{e_{max.}}{\omega L}$
λ	$\frac{1}{2}\lambda$	$\frac{2e_{max.}}{\omega L}$
		Transmission.
$\frac{1}{4}\lambda$	0	$\coth ah \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L} \simeq \frac{1}{ah} \cdot \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L}$
$\frac{1}{2}\lambda$	$\frac{1}{4}\lambda$	$\frac{\cosh ah/2}{\cosh ah} \cdot \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L} \simeq \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L}$
$\frac{3}{4}\lambda$	0	$\coth ah \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L} \simeq \frac{1}{ah} \cdot \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L}$
λ	$\frac{1}{4}\lambda$	$\frac{\cosh 3ah/4}{\cosh ah} \cdot \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L} \simeq \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L}$

The actual current distributions for $h = \frac{1}{4}\lambda$, $\frac{1}{2}\lambda$, $\frac{3}{4}\lambda$, and λ are shown and compared in Fig. 15. They are sinusoidal in all cases, but the receiving aerial is not in all cases the axis of symmetry of the curve representing the current distribution.

This latter feature is made more clear by considering the case $h = \lambda + h_0$, where h_0 lies between 0 and $\frac{1}{4}\lambda$. For this case

$$i_{max.} = \left(1 - \frac{\cos \pi x/\lambda}{\cos 2\pi h_0/\lambda}\right) \frac{e_{max.}}{\omega L}$$

so that $i_{max.} = 0$ when $x = h$, h_0, and $h - 2h_0$. The distance between the first and third nodes is λ, but between the first and second it is $2h_0$, which is not equal to $\frac{1}{2}\lambda$. The case is illustrated in Fig. 16.

For the transmitting aerial of the same height

$$i_{max.} = \sin \frac{2\pi}{\lambda}(h_0 - x) \cdot \frac{2\pi}{\lambda} \cdot \frac{e_{0max.}}{\omega L \cos 2\pi h_0/\lambda}$$

so that $i_{max.} = 0$ when $x = h_0$, $h_0 + \frac{1}{2}\lambda$, and $h_0 + \lambda$. The nodes are therefore $\frac{1}{2}\lambda$ apart. This is also illustrated in Fig. 15.

Actually in the cases where there is the greatest difference between the transmission and reception current distributions (i.e. $h = \frac{1}{4}\lambda$ and λ), the current is small compared with that corresponding to the quarter wavelength resonances. Thus the maximum current for $h = \frac{1}{4}\lambda$ is $\frac{1}{2}ah$ times that for $h = \frac{1}{2}\lambda$, probably about 10 to 1 in practice.

The cases considered, i.e. uniformly distributed e.m.f.

and point-source e.m.f., may be taken as extremes of possible variation of the distribution of e.m.f., and non-uniform distributions of e.m.f. will presumably give rise to current distributions intermediate between those described. In general, therefore, we may conclude that the current distribution is a function of the distribution of the exciting field, and that only in the special case of a single-point source of e.m.f. will it be safe to assume

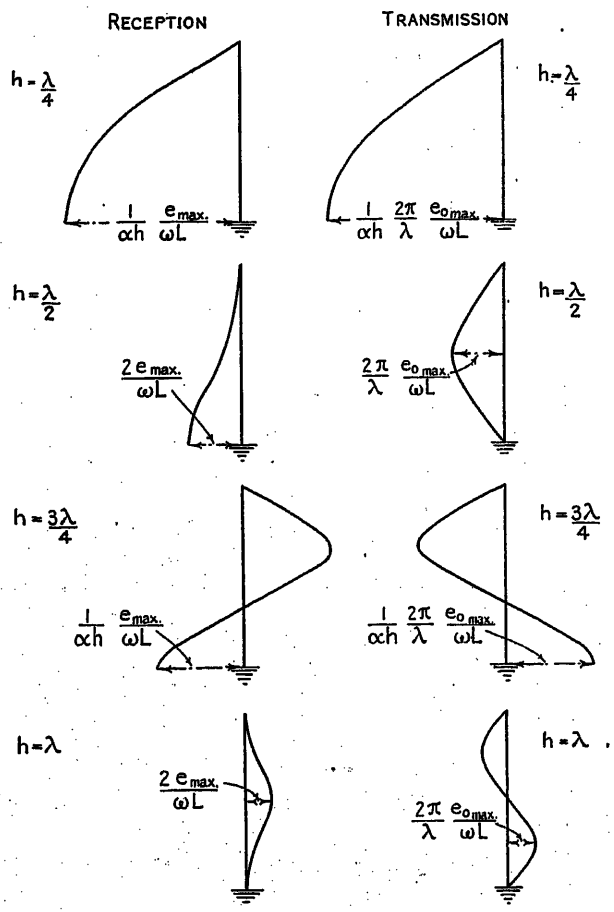


FIG. 15.

that the current nodes are separated by exact half wavelengths.

The distribution of potential is immediately derivable from the relation

$$v = -\frac{1}{j\omega C}\cdot\frac{\partial i}{\partial x}$$

which gives

$$\text{(Receiving)} \qquad v = \frac{e}{P}\cdot\frac{\sinh Px}{\cosh Ph}$$

$$\text{(Transmitting)} \qquad v = e_0\frac{\cosh P(h-x)}{\cosh Ph}$$

so that $v = 0$ and e_0 when $x = 0$ in the two cases respectively, as required by the assumed boundary conditions. The potential distributions are therefore not, in general, the same in the two cases, but in each case the distribution is sinusoidal (except for the small resistance effect), with half wavelength separation of successive nodes and antinodes. It should be pointed out, however, that this uniformity of separation of successive nodes depends on the assumption of uniformity of exciting field. In the more general case of a non-uniform field distribution a more complicated expression results for the current distribution—one containing e as a function of x, and e as a function of x will also appear in the expression for the voltage distribution. The matter does not permit of generalization, but in the absence of more detailed investigation there is no warrant for assuming uniformity of separation of successive nodes and antinodes of potential in the general case.

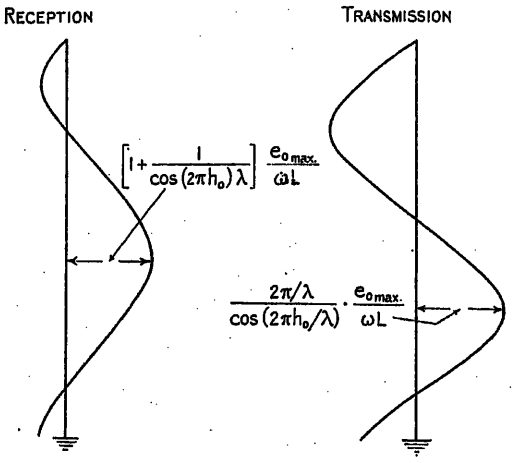


FIG. 16.

The author wishes to acknowledge his indebtedness to Mr. A. C. Gordon-Smith, who carried out practically the whole of the experimental work described, and to Dr. R. L. Smith-Rose for valuable criticism and advice on the compilation of the paper. The work was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scientific and Industrial Research.

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DISCUSSION ON

"INTERFERENCE BETWEEN POWER AND COMMUNICATION CIRCUITS: SUMMARY OF RECENT INFORMATION (1926 to 1929)." *

Mr. D. W. Roper (*communicated*): On page 1133 the author recommends that "when a high-tension 3-phase supply is transmitted by three single-conductor cables, these should be laid as close together as possible and transposed. Triangular spacing is preferable, but if flat spacing is adopted, regular transposition is essential." All of these recommendations are quite contrary to the practice in Chicago; therefore, in order to ascertain whether the author's recommendations found any warrant in American experience, I have corresponded with the engineers in charge of 66-kV and 132-kV single-conductor cable installations in New York, Philadelphia, Cleveland, and St. Louis, and with their assistance have prepared the following brief summary of practice and experience in the United States. In the cities I have mentioned, where all the 66-kV and 132-kV underground lines in this country are situated, there are now in service 109 miles of 132-kV and 485 miles of 66-kV single-conductor cables. The cables are laid in standard conduits in which the ducts have a spacing horizontally and vertically of about 6 or 7 inches. In no case is equilateral spacing adopted. The 132-kV cables in New York and Chicago are largely installed in a vertical row in conduits built especially for these lines. The use of special conduits for 66-kV cables is practically universal except in Chicago, where they are usually installed in the same conduit with lower-voltage cables. Local conditions determine whether the cables are installed in a vertical row, a horizontal row, or a right-angled triangle. Some of the underground lines in these cities are transposed, but there is never more than one complete transposition per line. The transpositions were made solely for the purposes of equalizing the power currents and voltages, not for eliminating or reducing inductive disturbances to adjacent telephone lines. In Chicago there are 10 telephone exchanges within ½ mile of our 66-kV single-conductor underground lines, and at numerous points the underground telephone cables run parallel to and cross these lines. The engineers of the telephone company were advised of the work on the earlier lines and were furnished with plans showing their routes, in order that they might make tests on the telephone lines most likely to be affected. Since the first power cables were placed in service in 1926, however, no adverse comment has been made regarding their influence on the telephone service. At the Midwinter Convention of the American I.E.E. held in New York in January 1931, a symposium of four papers† on the co-ordination of power and telephone plant, the joint work of the National Electric Light Association and the Bell Telephone System, was presented. No mention is made in these papers of any adverse effects of underground cables on underground telephone circuits. On the contrary, it is stated by Messrs. Harrison and Silver that the installations of 66-kV and 132-kV cable in this country "have a definitely favourable effect upon co-ordination problems within the territories surrounding them." If American practice had resulted in unsatisfactory co-ordination between power and telephone cables, it is inconceivable that all reference to such conditions would have been omitted from this discussion. It is considered good engineering practice to install telephone cables in separate conduits from power cables, and, where feasible, to install these conduit lines on opposite sides of the street. It is also customary to install high-voltage single-conductor cables for 3-phase transmission as close together as possible so as to reduce the induced sheath voltages or losses. Experience in this country indicates,

* Paper by Mr. W. G. RADLEY (see vol. 69, p. 1117).

† *Transactions of the American I.E.E.*, 1931, vol. 50, p. 437.

therefore, that when power cables and telephone cables are installed in accordance with good engineering practice there is no occasion to fear adverse inductive effects on the telephone circuits due to the power cables. Theoretical considerations and practical experience are in accord on the point that inductive effects are possible when the cables are separated by only a few feet and run parallel for a considerable distance. As such parallels are present, in general, along only a very small fraction of the total length of an underground transmission line, any rules which may be adopted as a result of the author's recommendations should be limited to that portion of the power line where the close parallel exists, as the extra expense of meeting the requirements at other portions of the line is entirely wasted.

Mr. W. G. Radley (*in reply*): The interference arising from power cables may often be reduced to negligible proportions by what Mr. Roper terms "good engineering practice," i.e. the installation of telephone cables in separate ducts and, where feasible, on the opposite side of the street. Were the circuits composed of overhead conductors such separations would not, in general, suffice. On account of the smaller conductor spacing and the screening effect of the cable sheaths, the transmission of power by cables instead of by overhead conductors must always assist in solving the problem of co-ordination between the two interests involved. The validity of Mr. Roper's contention that good engineering practice is a sufficient guide in the construction of an underground cable system, depends on the interpretation of the term. The "good engineering practice" of to-day becomes obsolete to-morrow, and it is not necessarily the same at one time under different conditions in different countries. One important difference in the present case is that in Great Britain the onus is on the power company to avoid interference, so that if it seems possible that interference arising at a future date would involve the power company in costly alterations, it is good engineering practice to avoid the risk, even if later experience proves the precaution to have been unnecessary. In effect Mr. Roper claims that from the point of view of interference with communication circuits it is not essential to lay three single-conductor cables as close together as possible, or to transpose them; though he admits that both these practices are customary in the United States for the purpose of reducing induced sheath voltages and balancing impedances. In this respect American practice supports the recommendations made in the paper. It happens that in Great Britain the direct method of laying cables, which has been preferred for reasons other than interference, permits of closer spacing than the duct system preferred in America; and the information available at the time the paper was written suggested that this feature could be made use of in minimizing the risk of interference. In the light of later knowledge and further experimental work, however, I agree with Mr. Roper that the spacing could be extended to that usual in duct systems without risk of greatly increasing interference. His record of practice and experience in America, particularly the joint experiments of the National Electric Light Association and the Bell Telephone System, is of great interest and value. A full account of these experiments would be very welcome.

DISCUSSION ON "COIL IGNITION SYSTEMS."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 8TH DECEMBER, 1931.

Prof. E. W. Marchant: I should like, first of all, to say something with regard to the question of magneto versus coil ignition. On page 105 (vol. 70) the author says:—"It is now generally recognized that the amount of energy delivered in the discharge by the ignition system, whether coil or magneto, bears no direct relation to the energy necessary for ignition of the explosive charge." I am sure that this statement is the result of much investigation, but most people must have come across the following difficulty when driving a car. I used to have a 4-cylinder car equipped with a magneto, and on long downhill stretches of road the plug on the cylinder nearest the front end of the car nearly always became gummed up, and had to be taken out and cleaned. I replaced that magneto by one capable of giving a rather larger power output, with the result that I had no more trouble due to gummed-up plugs. The reason, I think, is evident. Although the energy required for exploding the charge was no greater, the amount of energy in the spark was sufficient to stop carbon from accumulating at the plug and preventing the spark discharge from occurring. Therefore, although on theoretical grounds there is no necessity to have more than a limited amount of energy available for igniting the charge in the cylinder, in practice there seems to be a good deal of advantage in having some energy to spare, so as to ensure the regular firing of the engine. I have had experience with both magneto and coil ignition, and it is only after reading the paper that I have realized the limitations of coil ignition. There is much to be said for magneto ignition under certain circumstances. I have heard a good deal about the ignition troubles that occur in a damp tropical climate such as that of Nigeria. I think most cars are apt to give trouble in very damp climates, but the amount of trouble encountered with magneto ignition has been sensibly less than that with coils. The chief trouble in damp and tropical climates is that the battery is very apt to run down. A spare battery ought always to be available. Under these conditions I think there is still something to be said for magneto ignition, although, in general, coil ignition is more popular. I should like to ask whether there has ever been any suggestion of using condensers for the storage of energy, instead of inductances. Possibly a condenser might be a good thing to use because it can be charged up more quickly than the current can be established in an inductance. With regard to the coil itself, the reason why one cannot sensibly improve the operation of a coil by closing the magnetic circuit is because the losses go up as the amount of iron in the circuit increases. In this connection I am reminded of the "hedgehog" transformer designed by Swinburne about 35 or 40 years ago. Swinburne's theory was that the losses could be minimized by reducing the iron in the transformer by providing an air return circuit for the magnetic fluxes. In those days central station engineers did not mind so much about lagging currents as they do to-day. The open-core coil referred to in the paper is a development of the same kind. I presume there is a limit to the amount of iron one can use in the core, and that there is an amount of iron which gives the best results in the system. I am interested in the question of ballast resistances for regulating the current through the primary winding. Have iron resistances in glass tubes ever been tried, or are they thought to be too dangerous? They have extraordinarily good regulating qualities, and are used for all sorts of purposes in connection with thermionic valves.

Mr. Wilfred Holmes: I notice that the author mentions many limits, such as those set by heating, induction, and arcing. There is, however, another important limit, which arises when the battery voltage is nearly zero. This usually happens when the engine is cold and the oil has stiffened in the cylinder. The battery will then only give sufficient current to the starter motor to turn the engine very slowly, and the battery voltage becomes so low that there is not sufficient voltage to give a spark from the ignition coil. Laborious hand-winding of the engine then becomes necessary. Would the author advise another battery of small size in parallel with the starting battery, or is it practicable to have a couple of spare terminals with a disconnecting switch so that a small stand-by dry battery could be used for such an emergency? Probably this system would be cheaper than fitting a magneto, and it would have the advantage of low-speed starting.

Mr. S. R. Mellonie: The interesting devices described in the paper depend for their operation upon a primary supply of energy from a battery, which, in turn, is usually supplied by a small dynamo driven by the engine. Experience shows that the design of these small machines leaves much to be desired. In two machines recently examined the electrical creepage distance was only $\frac{1}{16}$ in. This was exposed on the outside of the machine to the mud thrown up from the road and on the inside to the carbon dust and copper particles which ultimately form a conducting path from the live brushgear to the earthed end-shield. In consequence of this weakness in the design the insulation of the two machines was burned away. Such clearances are obviously much too small and could easily be increased threefold without adding to the cost. Another curious characteristic of these small dynamos, which are usually of the 3-brush type, is overheating to such an extent that solder is thrown out of the armature on to the brushgear. It is generally understood that this is due to the third brush sticking in its holder, and if this is the case more attention should be given to

* Paper by Mr. E. A. WATSON (see vol. 70, page 105).

this feature of the design, as until such defects are remedied engineers are not likely to recommend the adoption of coil ignition systems.

Mr. J. B. Lees: Some time ago I bought four 1931-type 3-point plugs of a well-known make which proved to be very unsatisfactory. I returned them to the makers with a request to exchange them for single-point plugs, and received in reply the usual letter saying they saw no reason why the 3-point plugs should not be satisfactory. In answer I gave the following account of what I considered to be the cause of the trouble. The peak voltage becomes the breakdown voltage for a given set of gap conditions. The peak voltage must be proportional to the gap impedance, and, if we have three gaps in parallel as with a 3-point plug, the impedance will be lower than that of a single-point plug having the same gap dimension. The breakdown voltage of the 3-point gap will thus be lower, and the resultant arc will therefore not be so intense. I experimented with a 3-point plug at a pressure of 90 lb. per sq. in., and observed that at the instant of spark-over between the centre electrode and any of the three earthed ones, a brush discharge took place on the remaining two, thus indicating the lack of concentration of the available arc energy. Fig. 25 shows three oscillograms which would appear to confirm my suggestion, the reduction in peak voltage with reduction in impedance being clearly shown. I should be glad if the author would comment on my hypothesis and confirm that as a result of using a single-point instead of a 3-point plug, one would normally get a hotter spark. It may be of interest to add that the plug manufacturers agreed with me and sent me four single-point plugs, the operation of which proved to be absolutely satisfactory.

Mr. G. H. Sammons: During the War I supervised the maintenance of a large number of automobiles fitted with coil ignition systems. At that time American automobiles were mainly provided with coil ignition systems, while most of the British manufacturers still clung to the magneto. My experience was that the coil ignition system stood up better than the magneto to the rough usage to which these machines were subjected. Thus either the American system was inherently better for the purpose than the English system, or the American coil ignition system was better designed than the British magneto. In my opinion the workmanship and finish of the coil ignition systems was in general not so good as that of the magnetos. The coil ignition systems gave quite a lot of trouble due to wear of the distributors. The relays frequently stuck and caused the resistances and switchboards to burn out. At the end of three or four years there was very little left of the original coil ignition systems. Coil ignition systems have recently received a considerable amount of attention and research, and they are consequently very much improved. The chief trouble experienced nowadays with any ignition system is associated with the sparking plugs, and I think that if the sparking plug had received as much attention as the remainder of the ignition system, the performance of the system as a whole would be much more satisfactory. The performance of a coil ignition system depends almost entirely upon the condition of the battery, which as a rule is very bad. A central-station engineer spends hundreds of pounds a year in an endeavour to maintain his batteries in perfect condition, and by so doing he sometimes maintains his positive plates in good order for a period of 6 years. On the other hand, I am surprised that motor-car batteries last more than 2 years. It is much easier to repair a coil ignition system than a magneto. Another advantage of the coil over the magneto is that if the former is adopted it is possible to incorporate a device whereby the spark may be automatically advanced and retarded as the speed of the engine varies. There is no doubt that a system with an automatic adjustment has a distinct advantage over a fixed or a hand-operated system.

Dr. J. L. Miller: The author, referring to the possibility of developing loosely-coupled coils for coil ignition systems, states that one great disadvantage of having an arrangement which must be adjusted to correspond to optimum conditions is that these conditions would only hold for one particular type of sparking plug and one particular length of cable. The capacitance load of a length of h.t. lead and a plug would be rather uncertain, but I should think it would be of the order of 20 $\mu\mu$F. In view of the fact that the secondary capacitance is 100 $\mu\mu$F, small changes in the 20 $\mu\mu$F when the plug or lead was changed would not make much difference. At any rate, in the loosely-coupled circuits I have handled such a small change would not have made more than about 15 per cent difference. A great deal depends, of course, on the circuit constants, and I should be glad of the author's comments in this connection. Regarding the question of the primary condenser, it would be interesting to see an oscillogram giving the voltage wave-form across this apparatus, and to know the value of the maximum voltage reached. Can the author give the actual puncture values of the condensers used, and the voltage at which they are tested?

Mr. E. A. Watson (*in reply*): In reply to Prof. Marchant, the statement that the amount of energy delivered by the ignition system has no direct relation to the energy necessary for ignition of the explosive charge must not be confused with the phenomenon to which he refers, and which, I admit, is one well known among motorists. It is agreed, of course, that under conditions where a sparking plug is liable to oil up, the ignition system which will give a large amount of energy in the form of an arc or flame will burn away the oil and ensure regular ignition, but there is the other side of the picture to be taken into account, and that is the fact that this energy which burns away the carbon will also burn away the plug electrodes. The real remedy is so to arrange the plugs and the lubrication system as to prevent their receiving an excessive amount of oil under conditions such as those referred to, with the engine running on light throttle. I think that most modern cars, even with coil ignition, are fairly free from this trouble. Prof. Marchant mentions the use of a charged condenser as a means of energy storage. This has already been referred to in the paper and will be found on page 121 under the heading "Condenser and Transformer Systems." As regards the limit to the amount of iron that can be used in the core, this is

difficult to express exactly, but I think one may say briefly that if too much iron is used the coil becomes inefficient, with the result that the heating and sparking limits are reached, while if too little iron is employed the coil becomes expensive, owing to the large number of turns and the large amount of copper which is necessary, and the present-day coils are really a compromise between these. The suggestion of using an iron-wire resistance in a glass tube in hydrogen as a regulator has often been made, and such a resistance would be quite practicable. It is, however, rather more expensive than the open-type resistance generally employed, and present-day practice is in general to dispense with the resistance altogether.

In reply to Mr. Holmes, the limiting condition when the battery voltage is low has been taken into account in the paper. Of course, it is impossible to take this limit so low as to rule out absolutely all cases when the battery is very badly exhausted indeed, but with coils as designed to-day the battery has to be in a very bad condition before a spark cannot be obtained, and, although a spare battery substitutes an additional safeguard, I really do not think that its adoption is necessary.

Replying to Mr. Mellonie, the question of adequate creeping surface and adequate insulation was referred to in my reply to the London and Birmingham discussions, and will be found on page 134. I am naturally all in favour of adequate insulation being provided, even though the voltage is only a low one. The trouble to which Mr. Mellonie refers, of third-brush machines overheating, is not due to the third brush sticking in its holder, as the only effect of this would be to lift the brush off the commutator and break the field circuit, but it is generally due to the machine being run on open-circuit, possibly with the battery disconnected, so that the dynamo ceases to regulate and generates an excessive voltage, leading to overheating and burning out of field and armature winding.

Mr. Lees raises the question of 3-point versus single-point spark-gaps. I am afraid I cannot entirely accept his explanation. 3-point plugs for the same electrode dimensions have practically the same breakdown voltage as single-point plugs, but they have the advantage that there is less variation between the successive discharges, as the impulse ratio is less. For detailed information on this I must refer Mr. Lees to some of the published work on spark-gaps. The chief drawback of 3-point plugs is that under oily conditions, when incorrectly fitted, they are rather more liable to become short-circuited than the single-point plugs, but on the other hand their performance is more consistent and they last a good deal longer before burning away.

In reply to Mr. Sammons, I doubt whether his experience during the War, of the relative merits of coil and magneto ignition, can be taken as applying to present-day practice. In the first place the magnetos then available were either of American origin (and the Americans had very little experience in magneto manufacture), or, if they were made in this country, they were made by firms who were only just commencing magneto production, and who had, of necessity, to place all their best resources and experience at the disposal of the aircraft industry; but even so I note that Mr. Sammons goes on to state that the coil ignition systems gave a lot of trouble and that at the end of 3 or 4 years there was very little of them left. Mr. Sammons's remarks as regards batteries are certainly correct. The average motor-car battery, particularly on a private car, receives extremely bad treatment. It is sometimes grossly overcharged in summer, although not so frequently undercharged in the winter. On certain commercial vehicles and in particular in motor-bus services conditions are different, as the usual practice here is to fit a constant-voltage dynamo with a vibrating-type regulator, under which conditions the battery is much better treated and a substantially longer life is obtained.

Dr. Miller's remarks as regards the relative capacitance of the high-tension lead and the coil itself are, I think, substantially correct, although I should put the secondary capacitance of a modern coil as being rather lower than the figure he gives. It is not, however, only the capacitance which is likely to alter, but also the leakage loading, and this will, I think, have the same general effect. I am not able, at the moment, to publish an oscillogram giving the primary voltage wave-form, although I have actually made observations on this. Generally speaking, the primary-voltage wave is very similar to the secondary-voltage wave, and shows the existence of the high-frequency component due to the independent oscillation of the primary circuit impressed on the main fundamental oscillation due to the two circuits oscillating together. It is, of course, essential that the maximum voltage reached on the primary under any conditions should not exceed the figure at which a spark can pass across the contact points during the early stages of separation. Replying to Dr. Miller's query in regard to condenser puncture voltages, the usual figure is from 1 500 to 2 000 volts, the testing voltage varying between 500 and 1 000 for different manufacturers.

Scottish Centre, at Edinburgh, 26th January, 1932.

Prof. S. Parker Smith: The calculations associated with the design of a coil ignition system are difficult compared with those involved in the design of a turbo-alternator, transformer, or ordinary induction motor. Designers know that in general the smaller the unit, the more difficult are the calculations involved. One advantage of coil ignition is that a smaller starting set can be used with it than with the magneto. This is an important matter when one considers what a large percentage of the cost of the automobile goes to provide electrical equipment. The author has often drawn attention to the necessity of keeping the plug points properly adjusted and so avoiding the great danger to the insulation incurred by having too wide a spark-gap. With a coil the amount of plug adjustment necessary is usually far less than with a magneto. I have known a plug with multiple points burn away more quickly when used with a magneto than a single-electrode plug used with a coil. Apart from the risk of breakdown of the insulation, is there any such thing as plug deteriora-

tion, i.e. a progressive decrease in the efficiency of the sparking system with time? I should also like to know whether the fibre heel wears more rapidly than the contact points.

Dr. M. G. Say: I should be glad if the author would give a little more clearly the derivation of his equivalent circuit, with a diagram showing the assumed positive directions of the various currents and voltages. Without this the validity of the expression at the top of page 107 is not immediately apparent. This expression presumes negligible self-capacitance. Is this assumption justified? The capacitance C, referred to the secondary side, is given by $(C_2 + C_1/r^2)$. The ratio r may be 40 or more, so that even with a large primary (contact-breaker) capacitance the effect of the latter in the secondary must be comparatively small. Thus the secondary capacitance C_2 becomes the more important, and it must surely consist chiefly of self-capacitance, so that the voltage obtained at the secondary terminals is less than that given by the theory, quite apart from the effect of damping. It would appear that any reduction of the self-capacitance would be advantageous, in that the available energy would be more usefully employed in charging up the small external (plug and h.t. lead) capacitance to a higher voltage. If the author has available any oscillograms showing the growth of the primary current, their publication would be of interest. I should like to know what is the effect of sparking at the contact breaker. Presumably such sparking reduces the efficiency and available energy. It appears that if the contact-breaker condenser is too small, sparking occurs, whereas if too large it reduces the energy imparted to the secondary winding and in turn lowers the peak voltage reached. I should appreciate details of the wattmeter, electrostatic voltmeter, and rectifier valve shown in the test circuit of Fig. 27.

Mr. E. Seddon: The electrical ignition of the earlier type of internal-combustion engine was by means of trembler coils, then came the plain make-and-break, after this the magneto, and now we are back to the coil again. American cars, on the other hand, have always been fitted with coil ignition. The omission of the magneto drive no doubt makes for a quieter engine, and the majority of light 6-cylinder cars now appear to be fitted with coil ignition, but—possibly owing to mass production on cheap lines—the reliability of coils leaves much to be desired. I had only used my present car for a month when the coil broke down: I now carry a spare coil, as I have not as much confidence in this form of ignition as I had in the magneto. It is logical that a stationary piece of apparatus such as a coil should be the most reliable part of an engine unit, but I am afraid that the desire for cheapness makes it difficult for the makers to turn out a first-class article. I should like to ask the author which part of a coil is responsible for the largest number of failures: is it not the high-tension winding? The coil introduces a further weak link by placing more responsibility on that mechanically weak assembly, the accumulator. Now that the coil is replacing the magneto, it would seem desirable to run two separate sets of batteries in parallel in case of trouble. It is possible that one pair would still be in a sufficiently satisfactory condition to operate the coil, even if the other broke down. I should like to ask the author whether the coil could not be satisfactorily built-in with the distributor unit, in order to reduce the number of separate parts which have to be wired up. I should also like to know whether any experiments have been carried out with the rotary type of make-and-break, as at high speeds inertia causes difficulties in connection with all types of reciprocating motions.

Mr. E. R. L. Fitzpayne (*communicated*): I should like to give some statistics bearing on the question of magneto versus coil ignition. The City of Edinburgh Transport Department operates 61 omnibuses fitted with coil ignition; between May 1931 and January 1932 46 coils developed faults, 26 of these coils being under guarantee. The inconvenience caused thereby has not been as serious as it would at first appear, for each omnibus is fitted with two coils. When one coil becomes defective the driver connects up the other one. The remaining 90 omnibuses operated by the Department are fitted with magnetos, and over the same period 22 magneto failures occurred, but 200 magnetos had to be removed, dismantled, and overhauled in the ordinary course of maintenance. On our first coil-ignition omnibuses the coils were fitted in an enclosed box which was badly ventilated, causing overheating of the primary resistance. The box was earthed through the screws fixing it to the dashboard, and this arrangement also gave trouble by causing arcing at the points. However, when the box was properly earthed and ventilated no more trouble was experienced. The latest omnibuses have the coils fitted on an open board under the bonnet, and are much more satisfactory. In the paper the author states that the maximum current is obtained under low-speed conditions and also that voltages at starting are usually higher than at speed. This of course means that a good spark is obtained at starting —when it is most required—and is probably the reason why certain cars employ coil ignition for starting and magnetos for running. The author also states that the practice of mounting the condenser on the outside of the distributor is gradually being abandoned. In Edinburgh we have experienced so much trouble owing to the condenser becoming saturated with oil when inside the distributor, that we insist on its being outside. We still have some trouble owing to oil creeping into the distributor and getting on to the points, but we have eliminated it to a large extent by having an oil thrower fitted between the skew wheel drive and the spindle. On page 123 coil construction is described, and out of curiosity I therefore pulled a coil to pieces. This coil had a wire core, whilst round the primary was placed a plain tin sheath instead of the slotted and laminated iron sheath described by the author. In order to improve the performance of the petrol engine modern research is endeavouring to increase the compression ratio, and it would therefore be interesting to know how this will affect coil ignition.

Mr. E. A. Watson (*in reply*): Prof. Parker Smith's point as regards the burning away of plug points has been dealt with in my reply to Prof. Marchant. As regards progressive plug deterioration, I have never noticed actual deterioration of the insulation, other than by charring and roughening of the surface, permitting

of the deposition of a conducting film of carbon, although mica plugs will occasionally gradually develop leakage through the insulator itself, owing to disintegration of the mica under the effect of temperature-changes. As regards the wear of the fibre heel, the makers naturally endeavour to make the fibre heel and the contact points wear at equal rates, so as to avoid any readjustment.

In reply to Dr. Say, my assumption that the secondary self-capacitance is all concentrated at the end of the winding is doubtless not perfectly accurate, but I am afraid that if one endeavoured to take everything into account the mathematical considerations would become excessively involved. Dr. Say is quite right in saying that any reduction in self-capacitance would be advantageous, and I have always found it helpful in designing coils to aim at keeping this as low as possible. Generally speaking, to obtain a low self-capacitance necessitates increased thickness of insulation between the layers of the winding, which in effect increases diameter, the length of mean turn, and the cost of the copper, so that there is naturally an economic limit to this. The curves showing the growth of primary current to which Dr. Say refers are ordinary exponential curves and do not give any particular information, while the chief effect of sparking at the contact-breaker is to destroy the contact points and cause premature failure of the system.

Mr. Seddon will find the question of magnetos versus coil ignition systems dealt with on page 132, while as regards the point which he raises of failures in the high-tension winding I would say that in my experience the bulk of these have not been due to any attempt to cheapen the coil, but to lack of appreciation by manufacturers in the early days of the severe stresses caused by concentration of stress at the end-turns, due to the high-frequency surges produced at each spark. Modern coils, in which suitable reinforcement is used on the end-turns, are, like modern transformers, very reliable indeed. Mr. Seddon's suggestion of building the coil in with the distributor as one unit has often been put forward, but there are many constructional difficulties involved. After all, a coil has to be given certain dimensions, if only to enable it to radiate the heat if it is left on circuit, and these dimensions usually make it inconveniently large to combine with the distributor itself. Mr. Seddon's query as regards the use of the rotary-type make and break will be found answered on page 134.

I am very interested in Mr. Fitzpayne's statistics as regards service troubles on buses fitted with magneto and coil ignition. It is, of course, essential that the mounting of the coil should be given a certain amount of attention, and troubles can occur through incorrect mounting and insufficient ventilation, as the dissipation of a certain amount of heat must, of course, be provided for. I think that the coil which Mr. Fitzpayne took to pieces must have been of rather old design, as the use of sheet laminations for the core is practically universal to-day, while the sheath is either slotted, as indicated in the paper, or consists of two or three layers of thin metal superimposed. As regards the effect of increased compression ratio, this does not seriously affect the plug voltage, as in general increased compression ratio means a hotter-running plug, and the increased temperature of the electrode reduces the sparking voltage very nearly as much as it would be raised by the increase in compression.

Additional Communication to the Discussion.

Mr. J. Bethenod (*communicated*): I should like to point out that formulæ very similar to those of the author were derived in my paper "Sur l'allumage par batterie des moteurs à explosion" which was published in *Journal de la Société des Ingénieurs de l'Automobile* in June 1929, pp. 650–658.

Mr. E. A. Watson (*in reply*): I am indebted to Mr. Bethenod for drawing my attention to his previous paper, which had not come to my notice at the time my paper was written. I am interested to note that his results in general confirm my own—although he obtains a figure of 1·27 for a value of Rt/L in equation (3) on page 126 against my value of 1·256. This value must in the nature of things be a mathematical constant, and it would be interesting to know exactly what the value is. In my case it was only obtained through solution by trial of equation (2), while I fancy that in Mr. Bethenod's case it has been obtained by plotting the curve and taking the point at which it attains its maximum value.

DISCUSSION ON

" TWO TRANSMISSION-LINE PROBLEMS—SUSPENSION INSULATORS FOR INDUSTRIAL AREAS IN GREAT BRITAIN; CONDUCTOR VIBRATION." *

NORTH MIDLAND CENTRE, AT LEEDS, 12TH JANUARY, 1932.

Mr. S. R. Siviour: It is quite evident that the use of 4 discs in series on the 66-kV lines of the North-East Coast system gave too small a margin of safety. In this area we started with 5 discs on suspension sets and 6 on strain sets and these have given satisfaction, although regular cleaning is necessary at points subject to severe contamination. The nature of the deposit varies considerably with local conditions, but our chief trouble has been with an oily, tarry deposit: the amount varies considerably, even between insulators on the same pole, due to the shielding effect of the latter. I agree with the author's remarks on the British Standard Specification ratings, the flash-over values of which obviously refer to new, clean insulators, whereas when these insulators are tested after a short exposure under average service conditions they show greatly reduced flash-over values. Experience in industrial areas indicates that the wet flash-over voltage should be 60 to 70 per cent higher than the B.S.S. ratings. I should like to ask whether the line insulators concerned in the author's investigations were fitted with arcing rings or horns, and whether these materially affect the results. My experience is that flash-overs occur more frequently in the early morning or late evening, when presumably the equipment is covered with a film of moisture. Pollution appears to affect suspension sets chiefly: strain sets keep much cleaner and pin-type insulators are generally satisfactory if the design is right. We also find that cement-dust deposit is less serious than the oily, tarry deposit I have mentioned. As regards the proposed insulator (Fig. 5), I question the advisability of providing such deep overhung pockets between the fins. Regarding Part 2 of the paper, I should like to ask the author whether during his investigation into the problem of " stiction " he was able to trace the effects associated with steel-cored aluminium conductors and whether the results differ from those obtained with ordinary copper strand. It is generally understood that when steel-cored aluminium conductors are used regard must be had to the relative amount of the two metals. The author's demonstration of travelling waves in connection with the problem of conductor vibration reminds me of the so-called " dancing " conductors which some years ago kept two parallel lines out of use for several hours. The centres of the wires were at a vertical distance of 18 inches, and the vertical movement was such that the top and bottom wires were making periodic contact. The cause was sleet and ice loading under rapid changes of temperature, combined with an oblique wind: the majority of the binders held, but it was necessary to renew all of them and to adjust the sag. Does not the author's investigation lead to the conclusion that the addition of bird guards to insulators aggravates the flash-over difficulty? The material of which such guards are made has a surface which might collect dirt and possibly increase the risk of trouble. Bird guards can be eliminated by a suitable design of bracket which does not provide perches for the birds.

Mr. E. A. Logan: In common with the author I gained my first experience of overhead transmission in the neighbourhood of Newcastle-on-Tyne, and in consequence I was for a long time in the habit of regarding the detrimental deposition of dirt as normal to overhead-line insulators. At that time I thought that to overcome troubles arising from dirt deposits it was necessary to provide insulators of a size greatly in excess of that necessary to withstand with a large factor of safety the line voltage under wet test conditions. The precise effect of dirt in causing breakdown was then not fully appreciated, but breakdown was generally attributed to a covering of rain or mist over the whole of the leakage surface of the insulators not overhung by sheds. Acting on this assumption, with disc insulators it was decided to allow one more unit in tension or horizontal positions than in suspension or vertical positions, since it was supposed that the tension insulator could be wetted over its whole surface whilst the suspension insulator would remain dry on its under-side. Hence the 4 units and 5 units mentioned on page 806 as being provided on the N.E.S. Co.'s lines. This would have been quite logical had the insulators remained clean, but it was not anticipated that the unwashed surface of the suspension insulators would be fouled at the rapid rate which was, in fact, experienced. Very shortly after the lines had been put into commission, line patrols reported heavy discharges on certain lines at times of fog. Apparently, in the most affected situations sufficient dirt may be deposited in 3 months to cause trouble even in spite of the increased insulation resulting from the addition of the extra disc. I infer this from the statement on page 806 that the cost of cleaning is £5 per circuit per mile per cleaning, and that in the worst sections the annual cost is £20 per circuit-mile. I take it that this £5 per circuit per mile does not represent the whole cost to the supply authority, but only the cost of the labour and materials. In addition there will be the quite appreciable items of interest on idle transmission investment and the less tangible value of the loss of a line as part of a ring main, thus depriving some areas of a fully available duplicate supply and causing delay in restoring supply in the event of breakdown on another part of the circuit. Whilst the figure is not stated, the annual cost of all the cleaning, etc., necessary on the system must be considerable, and it should suffice to purchase and erect quite a number of the improved patterns of insulators. Since the paper was submitted to the Institution sufficient experience

* Paper by Mr. P. J. RYLE (see vol. 69, p. 805).

should have been obtained to permit the author to make a definite pronouncement on the relative merits of the two types illustrated in Figs. 5 and 6. The detrimental effect of the gaseous discharge from pulverized-fuel plants is of particular interest to the designers of super-power stations. The means of disposal of the electricity produced by a station is at least as important as the means of generation and, therefore, in these days of outdoor main switchgear and overhead outgoing main transmission it should be reasonable to allow a sum for the cost of additional insulation of these items when comparing a proposed pulverized-fuel system with other systems. Whilst for convenience of study of the problem discussed in Part 2 the author chooses to separate the small, relatively high-frequency, vertical oscillations of the conductor from the swinging movements, in practice one condition can, under suitable conditions, merge into the other and obscure or complicate the effects. One explanation of the vibration effect is that the force on the conductor arises from a lack of parallelism between the axis of the slip stream of the air behind the conductor and the streamlines of the general direction of the air flow which constitutes the breeze due to the formation of a non-symmetrical eddy. The conductor is thus responsible for causing a change of direction of the air flow, as a result of which it experiences a force. In general, the eddies form successively on alternate sides, but under special circumstances they may be maintained in a stable state on one side only, e.g. by causing the cylinder to rotate. The force thus becomes unidirectional. An example of the utilization of this unidirectional force is the so-called "rotor ship," which attracted a certain amount of Press comment some years ago. In this example the eddy was caused to remain in the air stream on one side of the cylinder by causing it to rotate, the resultant force being utilized to propel the vessel. An example of the formation of eddies on either side of a cylindrical body is provided by the flapping of a flag attached to a flagstaff. Here the flag waves in the breeze due to the eddies, which may be seen running along it. With regard to standing waves: a standing wave is the particular case of two travelling waves each of half amplitude travelling in opposite directions. Here the positive and negative energy-transfers along the wire obviously cancel out. The device suggested in Fig. 20 can apparently only act by causing bending of the conductor at the entrance to the clamp, and in this connection the author states: "It is obvious that this bending involves highly localized energy dissipation . . . and may be injurious to the cable." From this one would infer that the conductor clamp is not the best place at which to attach an energy-absorbing device, particularly as experience of actual conductor fracture and theoretical considerations alike indicate that the clamp, which is the only permanently nodal point on the line, is also the only potential danger point.

Mr. B. D. Youatt: Whereas the problem of the polluted overhead-line insulator is important, the danger arising from conductor vibration is not great where lines are designed for ice loading. We are accustomed to select our insulators on the basis of the B.S.I. tests, but these have nothing to say with regard to depreciation under operating conditions. Some form of pollution test with a specified minimum flash-over voltage is urgently required. A good deal of work has been done in this direction, but so far with no great measure of success. In Table 2 the author gives an indication of how this question might be dealt with. In that table he compares the total leakage resistance of different types of unit with the leakage resistance of their rain-washed portions. If the parts of an insulator which are shielded from rain and which therefore collect dirt were short-circuited by means of some conducting paint and then subjected to the standard rain test, the latter would probably give a better indication of their insulating value under operating conditions. A fog test would be preferable, but it is very difficult in practice to produce a convincing fog by artificial means. I note that the author does not subscribe to the theory that the electrostatic field appreciably affects the rate or extent of pollution. With regard to vibration, the theory that he puts forward to account for the limitation of amplitude by friction is interesting, as it explains the observations made by Varney and others that a vibration angle of 0·5° is rarely exceeded in practical cases. A solution of the problem of vibration which is not mentioned in the paper might be deduced from the methods adopted at sea in dealing with a similar trouble during the War. In order to counteract the danger from mines, paravanes were attached to the ship's bows by means of cables under considerable tension extending at right angles to the side of the ship. At first the vibrations produced in the cables securing the paravanes were so severe that they had a very short life. It was finally discovered that if the cables had a cross-section approximating to a triangle the vibrations were much reduced, and that considerable improvement was obtained if three cables were laid up to form one cable.

Mr. J. H. C. Brooking: I should like to refer to the three methods of overcoming trouble due to conductive deposits which have been tried in practice. The first, which consists in the use of more and deeper sheds, is stated by the author to have proved unsatisfactory in some cases. The second, that of increasing the size of the insulators, provides not only a longer but also a broader leakage path, and therefore affords wider scope for surface conductance. The third remedy proposed is to increase the area of the rain-washed portion of the insulator by putting the ridges outside, and this also has been criticized at previous discussions on the paper. A solution which does not appear to have been dealt with is that of considerably increasing the length of the surface path by extending the sides of the insulator in the form of sleeves covering the exposed part of the conductor adjacent to the insulator, or the suspension shackle of the string type. It may be that this suggestion has not been considered because of the limitations of porcelain, in regard to the likelihood of breakage by vibration of the wire where so enclosed, but it provides a possible method of getting over the trouble if the right kind of material is used. At the time of the salt storms in December 1928, my company heard from some users of Pernax bird-guards that wherever these were fitted to line insulators shut-downs of the lines did

not occur, whereas lines not equipped in this way were affected by the conductive condition of the atmosphere and thrown out of use. As a result of this experience a hood made of "Pernax" has been designed, which covers the whole of the porcelain insulator, whether of the pin or the shackle type, and thus prevents the conductive moisture from affecting its surface. Pernax seems to be less retentive of conductive moisture than porcelain. It may, however, not be due so much to the material or the design of the bird guard which is now incorporated in this insulator hood, as to covering up the live wire on each side of the insulator, thus keeping it at a great distance from the earthed pin or shackle. This form of bird guard has saved overhead lines from trouble during salt storms; the sleeves on either side provide a longer path for the current to traverse to earth. The top of the insulator is covered by the Pernax cap and is thus probably kept clean. A further type of bird guard has since been designed especially to cover the whole of the external surface of porcelain insulators on pins. The sleeves on either side cover a length of conductor also. They can be extended to any distance, because Pernax is not friable or likely to be broken by vibration. A lantern slide shows a string of eight insulators hooded with Pernax for use at 132 000 volts, and these sleeves also can be extended to any length on either side. The Central Electricity Board have decided to test this design at one of their stations. This type of hood for lessening conductive-deposit troubles can be made not only of Pernax, but also of any other highly insulating material that is unlikely to be broken by overhead-line vibration, and is not affected by the weather.

Mr. W. R. T. Skinner: With regard to the design of insulator shown in Fig. 5, would it be practicable to use a spiral groove on the outer surface, instead of a series of circular grooves? The circular grooves have to be sloped outwards and downwards in order to provide drainage, whereas a spiral groove would be self-draining even if the groove were sloped outwards and upwards. The information given in the paper leads me to think that an upward sloping groove might be even more effectively cleaned than one with a downward slope. The scouring action of water draining down the spiral groove should be considerable.

Mr. C. R. Clarke: It appears that the so-called "suspension" insulator has given no trouble when used as a tension member, and I therefore see no reason why the two surfaces of a tension unit should not be similar. Could not both surfaces be corrugated, and, if so, would it then be possible to dispense with one unit of a string, giving an increased clean leakage surface?

Mr. R. G. Ward: I should like to ask two somewhat simple questions. First, the author mentions that "Pyrex" has been used for insulators; I take it that he refers to the electrical resistant glass. Has any other kind of glass been tried, and why particularly was Pyrex used? I have always been led to understand that glass is one of the best insulators, and in this case it will probably be one of the worst for collecting dirt of the type which accumulates on the under-side of an insulator. My second question is: What is the effect on the conductor when it gets into a swing similar to that which the author obtained with a chain? Is there any tendency to unwind the strands?

Mr. E. A. Mills: I should like to inquire the object of corrugating the suspension insulator shown in Fig. 5, as in view of the tendency of dirt to collect on the under-sides of the corrugations a smooth surface would appear to provide better results. Corrugations on any form of insulator are difficult to clean, and I feel that it is a retrograde step to introduce them on insulators of modern design.

Mr. P. J. Ryle (*in reply*): Mr. Siviour mentions that, in the Yorkshire Electric Power Co.'s area, the chief trouble has been from the oily, tarry type of deposit, and that the intensity of deposit varies greatly even on insulators on the same pole. The paper is intended to give a general review of the problem, and no detailed consideration is given to different types of industrial deposit or to different degrees of fouling. My experience is similar to Mr. Siviour's in regard to the surprising degree of non-uniformity of deposit intensity which is often noticed in a given area. I think Mr. Siviour's estimate of 60 per cent to 70 per cent over British Standard Specification ratings is a little pessimistic and I am of the opinion that, for pin-type insulators of normal shapes, 50 per cent would probably be a reasonable margin. At the same time it must be reiterated that the wet flash-over test is not necessarily a good guide to the performance of insulators in dirty areas. In my opinion it is not improbable that insulators could be made of such shapes that they only just complied with the British Standard requirements, whilst giving much better service results than standard shapes designed to meet the same wet flash-over specification. I do not think that arcing rings or horns would have any appreciable effect, one way or the other, on the performance of insulators up to, say, 66 kV. At 132 kV and upwards, arcing rings may be of some benefit since they help to equalize the voltage per unit of the long insulator strings. Without such rings, the last unit of a 132-kV string may have to carry 25 to 30 per cent of the total voltage and therefore may be a very weak link in the electrical chain. On the other hand, when insulators are heavily coated with semi-conducting deposits there is already a considerable self-equalization of voltage over the string, so that the arcing ring may not be of much additional benefit. The chief aim of arcing horns and rings is to minimize damage to the conductor and the insulator string itself caused by the power-arc following flash-over. With regard to Fig. 5, several speakers have been under the impression that the external ribs are overhung. This is not so. Fig. 5 is, perhaps, misleading in this respect, and Fig. O is given on page 262 to show, to a larger scale, the actual shapes of these ribs as adopted on the insulators now undergoing trial. On the Newcastle Electric Supply Co.'s system I do not think that bird guards have had any appreciable effect on tendency to flash-over. On the 66-kV lines no bird guards have been used, and on the lower-voltage (pin insulator) lines the bird guards, where used, have been of types fixed to the cross-arms only. For the last three or four years bird guards have been entirely abandoned, except on certain special switching poles, etc., and complete im-

munity against bird troubles has so far been given by tilted cross-arms on which birds will not perch. With regard to Part 2 of the paper, my discussion of inter-strand friction and its effects is so far entirely theoretical, and I have not yet had opportunity to carry out any experimental work on the subject. There is no doubt that the effects would vary with different conductor materials, as well as with different strand diameters, angles of lay, etc., as will be evident from a study of Appendices I and II. Mr. Siviour's experience of " dancing " conductors, whilst not within the scope of the paper, is of interest. I have known a case where " dancing " must have been the cause of clashing which definitely occurred between conductors at 4 ft. vertical spacing (400-ft. spans, 0·1 sq. in. copper conductors). In this case there was no question of sleet or rapid temperature-changes. The phenomenon occurred on two different dates, at a certain individual span, each time putting the line out of service. On both occasions there was a high wind, but the phenomenon was not actually observed by anyone. After the second occasion I made a point of visiting the particular span several times when high winds were blowing but saw no signs of dancing, the conductors merely being blown out of the vertical and remaining steadily in their normal relative positions. So far, the phenomena of " dancing " are far more obscure than those of vibration as defined at the beginning of Part 2 of the paper.

Mr. Logan infers that the approximate costs of insulator cleaning given on page 806 (vol. 69) are only inclusive of actual labour and materials. This is correct, and he rightly calls attention to the less tangible costs which may have to be borne by the supply authority, such as interest on idle capital investment and temporary loss of service reliability owing to non-availability of complete duplicate supply. In some cases one might also include cost of additional copper losses where both circuits of a double-circuit line, or both sides of a ring are normally maintained in service. Of course, many such incidental costs would usually not be very serious since cleaning would be confined to week-ends or times of light load, and the work can always be called off at, say, half an hour's notice, if necessary. On this subject, I would refer Mr. Logan to Mr. Stedman's contribution to the discussion at Newcastle. It becomes very obvious that the industry could well afford to pay for a large amount of serious research on the subject. I agree, in principle, with Mr. Logan's suggestion that in comparing a projected pulverized-fuel station with an ordinary coal station something should be allowed for the additional cost of outdoor insulation required for the former. Since, however, we know neither how far from the station the polluting effects may be serious nor, in the present state of knowledge, what improved insulation to use, no very reliable estimate could be made. In actual fact the additional cost of any improved insulation would probably be very small in comparison with the total power-station costs. As regards service performance of the insulators shown in Figs. 5 and 6, 36 strings of 5 units of each type have now been in service on lines for a year without trouble. A string of 4 units of each type has also been kept alive on the testing rack for well over a year without flash-over. None of these special insulators has been cleaned, but in the period under review dirt pollution has been less than normal owing to the industrial depression, and unusually few serious fogs have occurred in the district. Little definite information has therefore yet been obtained, except that either type of insulator is, in itself, quite satisfactory for normal operation. Mr. Logan's remarks on eddy formation in Part 2 of the paper summarize clearly the phenomena involved. It is, unfortunately, impracticable to rotate overhead line conductors, but the formation of stable eddies on one side of the conductor only could also be obtained by the use of specially shaped (non-circular) conductors. A brief reference to this solution in connection with paravane towing cables is made on page 812 of the paper. I believe that the use of non-circular conductors is actually being considered in the United States for certain future 220-kV lines. There would be no great difficulties in manufacturing such cables, but serious difficulties arise in connection with fittings, especially the tension clamps and joints. Mr. Logan's reference to the visual illustration of eddy formation by a flag pole and flag is extremely interesting, but it is possible that the flag itself may have something to do with the eddy formation. A flag attached to a fine taut wire, instead of to a pole, would probably show evidence of non-stability of air flow. Mr. Logan's conception of standing waves is identical with that indicated in my reply to Prof. Thornton at Newcastle. With regard to the device shown in Fig. 20 I agree that the clamp is not the best place for a true anti-vibration device, but it is a convenient place and one not introducing any new " hard-spots " or points of possible risk due to clamping indentations. A hydraulic damper, if one could be made to have ideal characteristics, might act in such a way that no appreciable vibration amplitudes would ever build up. If this were the case, the fact that it added to the mass associated with the clamp would be of no importance.

Mr. Youatt implies that the risks of conductor vibration, where the lines are designed for ice-loading, are not very great. In general, I agree, but heavy vibrations are frequently observable on large-conductor lines in this country and I have recently had my attention called to various minor troubles such as loosening of bolts on insulator fittings, and even breakages of certain parts where trouble would never be expected. Time alone can show whether or not the conductors of any particular type of line will stand up to the effects of vibration. I agree with Mr. Youatt that some standard pollution test for insulators is very desirable, but can see no possibility of formulating such a test in the present state of knowledge. The proposal to paint those parts of insulators which normally collect most deposit with conducting paint prior to rain or mist flash-over tests, is of considerable interest and might lead to useful information on the relative values of insulators of widely different shapes. In connection with cables of non-circular section I would refer Mr. Youatt to my reply to Mr. Logan.

Mr. Brooking refers to the possible use of " Pernax " or similar material for covering, wholly or partly, the

insulator and also covering the line conductor at either side of the insulator with a view to lengthening the leakage path to any desired extent. This suggestion, although at first sight revolutionary, is not to be summarily dismissed and I hope that Mr. Brooking will follow it up by research and test. If a pin-type insulator or suspension string were to be completely enclosed in a "Pernax" shield, it might be difficult to ensure satisfactory service under heavy rain, and new troubles might be introduced by moisture condensation or by air ionization inside the enclosing shield.

Mr. Skinner suggests a suspension unit generally similar to that shown in Fig. 5, but with an upwardly-opening spiral groove. Messrs. Steatite and Porcelain Products, Ltd., have already made experimental units of this type, and a string of four units is now on the testing rack at North Tees. This string has, so far, only been alive for a few months, but without flash-over. There is a slight tendency for dirt to collect in the bottom of the groove, presumably due to rain washing it off the sides of the groove and leaving it at the bottom when drying. It would need a very heavy rain indeed to produce anything like a scouring action at the groove bottom.

In reply to Mr. Clarke, there is no reason why both surfaces of a tension unit should not be similar and corrugated, if necessary, excepting, possibly, certain manufacturing difficulties and the fact that since tension strings of normal units give good service there would be no incentive to manufacture units of non-standard and probably expensive design. Some development work is, however, being done on tension units designed to give the maximum rain-washed surface.

In reply to Mr. Ward, I have no direct experience of either "Pyrex" or ordinary glass suspension insulators, except that a string of purely experimental "Pyrex" insulators is erected on the testing rack. There are fields of use for both "Pyrex" and ordinary glass pin-type insulators to-day, but, as far as I am aware, these materials have not yet proved themselves suitable for disc-type insulators owing to mechanical-strength requirements. From visual examination, only, of the experimental strings on the testing rack, "Pyrex" appears to be neither better nor worse than porcelain from the point of view of collecting dirt deposits. Referring to the experimental demonstration of rotating waves (see Appendix III of the paper), although the loops rotate, the chain itself does not revolve and there is no twisting action. For instance, in demonstration (*b*) one end of the chain is held firmly in the hand and the other is held on a fixed hook so that there can be no rotation or twisting of the chain itself. The vibrations of a transmission-line conductor are usually plane or nearly so. This can sometimes be seen very well at a tension string on a 132-kV line where a circular guard ring is attached to the line end of the string. Under suitable conditions of heavy vibration the oscillations of the guard ring clearly indicate the vertical plane of the conductor vibrations. The top and bottom of the guard ring appear blurred, whilst points on the horizontal centre line across the guard ring remain perfectly clear.

In reply to Mr. Mills, the object of corrugating the upper surface of the insulator shown in Fig. 5 is that of increasing the length of the clean, and therefore most effective, part of the leakage path. There is practically

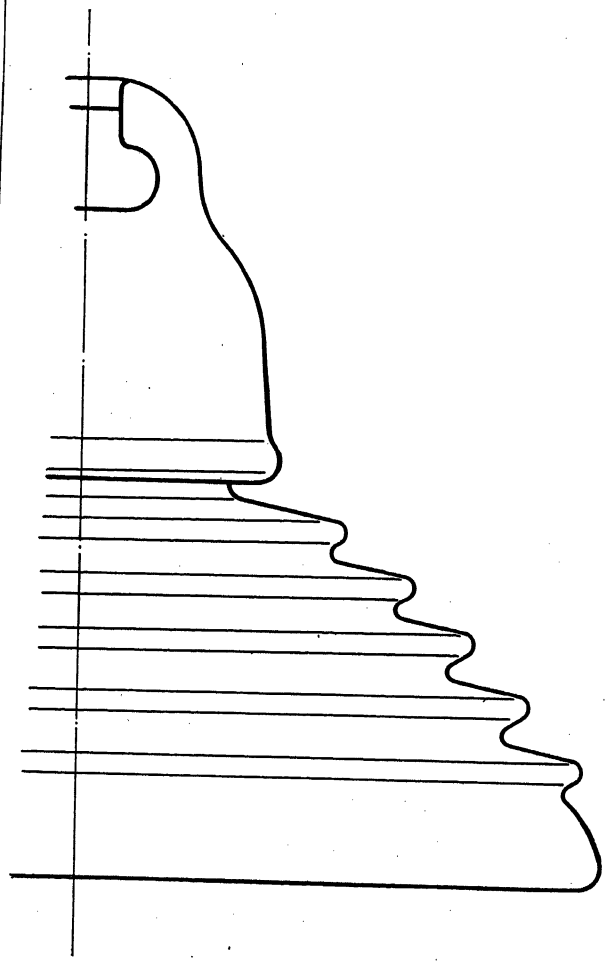


FIG. O.—Enlarged view of suggested suspension insulator shown in Fig. 5 of paper.

no tendency for dirt to collect in the non-overhung grooves on the upper surface, and I would refer Mr. Mills to col. 1 on page 810 of the paper, to my replies to Mr. Langton and Mr. Farrer (pages 846 and 847), and to Fig. O referred to in my reply to Mr. Siviour. Incidentally, when insulators of this form do require cleaning the cleaning of the external corrugations is very easy, and presents a problem very different from that of cleaning the corrugations on the under-sides of standard insulators, especially those nearest the central pin.

HEAT LOSSES DUE TO LOAD CURRENT IN DIRECT-CURRENT ARMATURE WINDINGS.*

By E. A. HANNEY, M.Eng., Associate Member.

(*Paper first received* 18*th August, and in final form* 31*st December*, 1931.)

SUMMARY.

Designers of alternating-current machinery have long been able to make rapid estimates, by means of published curves, of the heating effect due to current displacement in slot-wound conductors. The wave-shape of the current in the windings of direct-current armatures is complex, since it is rich in harmonics. The estimation of the heating effect due to current displacement in direct-current armatures has hitherto necessitated laborious calculation, for each case on its own merits. The busy designer rarely has the time to carry out such a long process, and it is probable that in most cases guesswork is resorted to.

In this paper an attempt is made to provide curves, by the use of which the heating of direct-current armatures may be estimated rapidly. It is believed that results are obtainable with fair accuracy, and with almost the same rapidity as is associated with the estimation of the loss in an alternating-current machine. It is not possible to construct one curve for use in all cases; a "standard" curve is given, which refers to a single-turn full-pitch winding, having 15 slots per pole and 45 commutator segments per pole. Two additional curves give coefficients which enable other full-pitch single-turn windings to be dealt with. The heating ratios so obtained do not differ from those obtained from individual calculations by more than 2 per cent in any practical case. Curves are also given for windings which differ from the standard winding in having (*a*) two turns per coil, (*b*) three turns per coil, (*c*) chording. The question of the critical height of conductor, and the question of the use of unequal heights for the two layers in a slot, are also touched upon.

It is, perhaps, not generally realized that current displacement is present at all times in a direct-current armature winding; it is not confined to the period of commutation. A set of current-distribution curves has been calculated for one case, to show this.

The author hopes to deal with the problem of the rotary convertor, and the problem of unusual winding arrangements designed to reduce heating losses, in a subsequent paper.

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(4) The Method of Calculation of the Heat Loss.
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II. Calculated Values of M_r and N_r.
III. A Selection of the Values of K_0 calculated for Full-Pitch Single-Turn Windings.

LIST OF SYMBOLS.

f = frequency of a periodic function, cycles per second.
h = height of one conductor, cm (see Fig. 6).
I_c = maximum current (amperes) in one conductor of a direct-current armature winding.
$\mathbf{I}_1$ = vector notation of a sinusoidal current component, of amplitude I_1.
i_b, I_b, $\mathbf{I}_b$ = total current flowing in a slot below the conductor in question.
K = ratio between the heat loss due to a sinusoidal alternating current, and the loss which would occur if the current were uniformly distributed throughout the conductor.
K_n = K when specifically applied to the nth harmonic of the trapezoidal current [see Fig. 2(*b*)] of maximum value I_c.
K'_n = ratio between the heat loss due to the nth harmonic of the trapezoidal current of maximum value I_c, and that due to a steady current I_c (see Section 4).
K_0 = ratio between the heat loss due to the trapezoidal current of maximum value I_c, and that due to a steady current I_c. $K_0 = \Sigma K'_n$.
l = buried length of one conductor, in cm.
l_1 = total length of one conductor, i.e. active length + length of end connection.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

List of Symbols—*continued.*

$\mathbf{M} = ah \coth ah = M_r + jM_x$ (see Section 4).
$\mathbf{N} = 2ah \tanh \frac{1}{2}ah = N_r + jN_x$ (see Section 4).
n = order of harmonic.
n_a = number of coil-sides side by side in a layer in one slot (see Fig. 1).
p = the number of a conductor in one coil-side of a layer, counting from the bottom of the layer (see Fig. 1).
s = number of turns per coil in the winding, i.e. conductors in series per coil-side (see Fig. 1).
t = time, in seconds.
w_c = total width of conducting material in one layer across the width of the slot, in cm ($w_c = n_a \times$ width of one conductor).
w_s = width of slot, in cm (see Fig. 6).
x = height of a level in a conductor, measured from the boundary of the conductor remote from the slot mouth (see Fig. 6).
a = a "semi-imaginary" quantity; $a = |a|\underline{/45°}$ (see Section 3). Except where expressly stated in Section (3), a is calculated for the fundamental, of angular velocity ω.
$|a|$ = numerical value of a; a function of f, w_c, w_s, ρ (see Section 3).
2β = angular width of commutating zone for one coil; an electrical angle based on the pole-pitch as angle π (see Fig. 2).
Δ = instantaneous current density, amperes per cm^2.
Δ_x = vector notation of sinusoidal component of current density, at height x in a conductor.
θ = phase angle ωt.
ρ = resistivity of the conductor material in C.G.S. units.
ϕ = phase angle between two sinusoidal currents, of the same frequency, in corresponding coil-sides of the two layers in a slot. (ϕ = zero for full-pitch windings.)
2ψ = electrical angle between adjacent currents in two neighbouring coil-sides of a layer in one slot, based on the pole-pitch as angle π (i.e. electrical angle between two commutator segments).
ω = angular velocity of the fundamental component of the current wave of maximum value I_c, in radians per second.

Introduction.

Whenever the current in a conductor is varying, a displacement takes place so that the distribution of current in the conductor is no longer uniform. The heat for which a non-uniform current is responsible is greater than that which accompanies the same current if the distribution is rendered uniform.

The heat loss which takes place in the buried conductors of a winding carrying a sinusoidal alternating current was first investigated by A. B. Field,* whose results have been of great use to designers.

The fact that a somewhat similar current displacement takes place in the armature conductors of a direct-current machine has for some time been appreciated.* The investigation of individual cases has, however, necessitated very laborious calculations.

In this paper the author has endeavoured to present data from which the effective resistance of the buried portion of the armature winding of any normal direct-current machine can be predicted with an accuracy sufficient for engineering purposes. The method of presenting the data is such that results should be obtainable with no more labour than is associated with similar calculations for the alternating-current case.

The general method of computing the total loss in a conductor carrying a non-sinusoidal alternating current which flows in a direct-current armature is as follows:—

The wave-shape of current is replaced by a Fourier series and the loss due to each harmonic is determined separately. (The above Fourier series is infinite, but the resultant loss series has fairly rapid convergency in normal cases.) The justification for the separate treatment of the harmonics, and the summation of the terms of the resultant loss series, is capable of rigid proof.

In general it is unlikely that the heat loss due to the displaced current of a loaded direct-current armature can be predicted as closely as that of an alternating-current armature. Three important causes militate against accurate predetermination. They are:—

(1) Uncertainty of current wave-form, which may be influenced by brush contacts, interpole adjustment, brush position, etc. This matter is considered in Section (1).

(2) Phase difference between neighbouring currents in one layer of a slot. This is considered in Section (2) below.

(3) Doubtful accuracy of calculations for harmonics of high order. This arises from the phase difference between neighbouring currents (see the preceding cause), and to the uncertainty regarding tooth saturation and tooth eddy losses at the higher frequencies.

It must be noted that the fundamental and the lower harmonics always contribute an overwhelming proportion of the total loss. It will be seen below that the uncertainties referred to above appear to exist in a marked degree only in the case of harmonics which are negligible, in their contribution to the total loss.

Definition of Terms applied to Windings.

There is no standard nomenclature applied to the windings of dynamo-electric machines. It is therefore necessary to define the terms used in this paper in regard to the windings of direct-current machines.

A direct-current armature winding, as ordinarily arranged, is regarded as being of the *two-layer type*. The layer nearer the mouth of the slot is referred to as the *upper* layer; that near the bottom of the slot is referred to as the *lower* layer. The conductors in one layer in one slot are all taped together to form one *taped-up coil*; one side of a taped-up coil constitutes the upper layer in some slot, and the other side of the same taped-up coil constitutes the lower layer in some other slot. But one taped-up coil usually consists of several exactly similar coils, arranged side by side in the taped-up coil; corresponding ends of neighbouring coils are con-

* See Bibliography, (1).

* See Bibliography, (34) to (43); also part of (2), and (10) (Part III).

nected to neighbouring commutator segments. Each coil may have a number of turns, arranged one above the other; the conductors of the several turns of one coil constitute a *coil-side*.

The symbol n_a is used for the number of coil-sides side by side in one taped-up coil. A multi-turn coil is described as having s turns. The turns are always counted from the bottom of a layer towards the mouth of a slot, and reference is made to the pth turn. The value of p applied to any one conductor applies only in

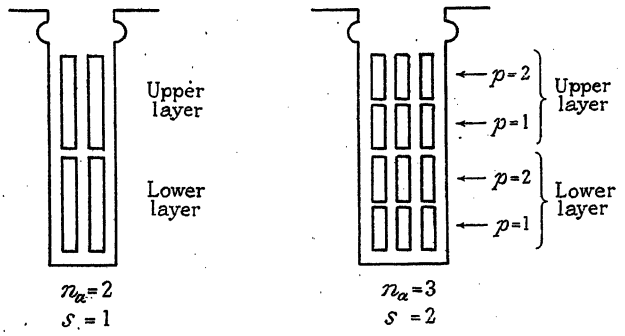


FIG. 1.—Examples of arrangements of windings in slots.

the slot under consideration (thus one side of one turn may be the top turn in the upper layer of one slot, whilst the other side of the same turn is the bottom turn of the lower layer of another slot).

Examples of arrangements of windings in slots, showing the application of the nomenclature, are given in Fig. 1.

(1) THE CURRENT WAVE-SHAPE AND ITS HARMONICS.

The simplest assumption regarding the wave-shape of the current in the conductors of a direct-current armature is a rectangular wave, in which the current has its

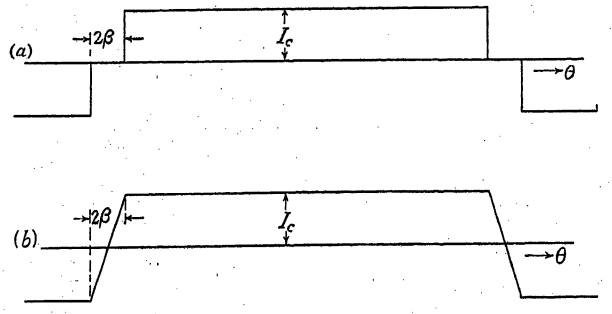


FIG. 2.

maximum value for a complete half-period, the reversal being instantaneous.

Another approximation is to assume zero current during the time interval in which the coil undergoing commutation is short-circuited. This is shown in Fig. 2(*a*).*

A further simple wave-form is that in which the current changes during the time of commutation according to a straight line (Fig. 2*b*).

* This wave-shape is included since it is the basic form from which other wave-shapes are derived by adding a wave representing the behaviour during commutation. Also this wave-shape is stated by W. V. Lyon [see Bibliography, (41)] to be the one on which the nominal resistance loss should be computed, according to the Standardization Rules of the American I.E.E.

In practice the way in which the current changes during the period of commutation is uncertain. It is greatly influenced by the design of the interpole, and is likely to be different for the various coil-sides of a layer. The actual wave-form always consists of that of Fig. 2(*a*), plus a wave-form in which the current is zero except during an interval 2β in the half period. Thus the behaviour of the current during the period of commutation cannot greatly affect the amplitudes of the lower harmonics in any practical case.

An investigation has been carried out on several simple wave-forms. These include the rectangular wave-form, those of Fig. 2, and forms in which the current changes during the period of commutation according to a half-period cosine wave, and to quarter-period sine waves representing accelerated and retarded commutation. In all waves except the rectangular one it was assumed that $2\beta = 12$ fundamental electrical degrees (i.e. a commutation period occupying 1/15th of the half period). Excluding the rectangular wave, and that of Fig. 2(*a*), the amplitudes of the higher harmonics differ, as between the several wave-forms, by amounts which do not exceed about 1 per cent of the fundamental.

The heating effects due to given harmonics are proportional to the squares of the amplitudes. It is therefore clear that the type of commutation on which calculations are based is not of much moment. At the same time, the rectangular wave-form, and that of Fig. 2(*a*), are extreme cases which bear no relation to practice.

The author therefore decided to base all calculations on straight-line commutation (Fig. 2*b*).

(2) THE PHASE DISPLACEMENT BETWEEN NEIGHBOURING CURRENTS IN A LAYER.

The fact that there is a phase displacement between the currents in neighbouring coil-sides in a layer complicates the distribution of magnetic flux within the slot. It will now be shown that the effect of ignoring this complication cannot introduce a large error in any practical case.

If straight-line commutation is assumed, the current in one coil-side varies according to Fig. 3, in which the angles correspond to the fundamental. Thus 2β is the angular width of the commutating zone for one coil, and I_c is the maximum value of current per conductor.

Mathematically this current may be represented by

$$i_1 = \frac{4}{\pi} I_c \left[\frac{\sin\beta}{\beta} \sin\theta + \frac{1}{3} \frac{\sin 3\beta}{3\beta} \sin 3\theta + \ldots \right]$$

The current in an adjacent coil-side in the same layer is

$$i_2 = \frac{4}{\pi} I_c \left[\frac{\sin\beta}{\beta} \sin(\theta - 2\psi) + \frac{1}{3} \frac{\sin 3\beta}{3\beta} \sin 3(\theta - 2\psi) + \ldots \right]$$

where 2ψ = the fundamental angle between two neighbouring coil-sides or commutator segments.

If there are n_a coil-sides per layer in one slot, the fundamental phase angle between two limiting coil-sides in a layer is $2\psi(n_a - 1)$. The corresponding angle for the nth harmonic is $2\psi n(n_a - 1)$.

When a sinusoidal current of frequency n times that of the fundamental, and of amplitude $\left(\frac{4}{\pi} I_c \frac{1}{n} \frac{\sin n\beta}{n\beta}\right)$, traverses each of the n_a coil-sides of a layer, with a phase displacement 2ψ between two neighbouring coil-sides, the resultant current of the layer is

$$\frac{4}{\pi} I_c n_a s \left(\frac{1}{n} \frac{\sin n\beta}{n\beta}\right) \left(\frac{\sin n_a \psi n}{n_a \sin \psi n}\right)$$

where there are s turns per coil.

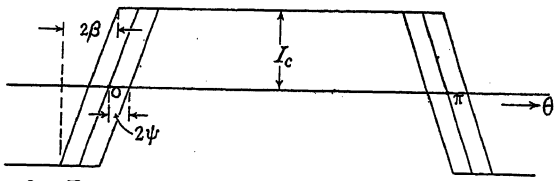


FIG. 3.—Trapezoidal current wave-forms in adjacent coil-sides.

Both the quantities within brackets decrease for increasing values of n. (They both decrease to zero and become negative, but this occurs at stages which, for the general practical case, are beyond the significant limits.)

The "Transverse" and "Radial" M.M.F.'s of a Layer.

The resultant current of a layer in one slot gives a magnetomotive force which is directed across the slot. This "transverse" m.m.f. tends to produce a flux which is normal to the sides of the slot.

The components of the individual sinusoidal currents which are in time quadrature with the sinusoidal

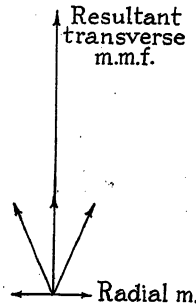


FIG. 4.—Individual, resultant transverse, and resultant radial m.m.f.'s due to a harmonic of the currents in the coil-sides of a layer in one slot ($n_a = 3$).

resultant, cancel one another. But these components have an actual existence on the two sides of the centre-line of a slot. The sum of these components on one side of the centre-line of a slot gives the current which produces the "radial" m.m.f. acting along that centre-line. (It is at once evident that, in any given slot, or layer in some slot, in a direct-current armature, "radial" m.m.f. can only exist whilst commutation is taking place within the given region, for at all other instants all coil-sides within the region carry the same current. Thus the "radial" m.m.f.'s due to sinusoidal components of the total current cancel one another except during brief intervals. This is further considered below.)

The simple case of three coil-sides per layer in one slot, carrying sinusoidal currents which differ in phase (as in the case of a harmonic of the currents in a direct-current winding), is illustrated vectorially in Fig. 4. The figure shows the transverse and radial m.m.f.'s.

One of the most important premises* in the investigations first carried out by A. B. Field is not observed in a winding where a radial m.m.f. is able to upset the field normal to the sides of the slot. It is therefore necessary to make some attempt to assess the influence of this radial m.m.f. in practical cases.

The Magnitude of the Radial M.M.F.

It is of interest to examine a case in which the radial m.m.f. is unusually large. Such a case is furnished by a slot containing only two coil-sides per layer, when the fundamental phase angle between them, and the width of the commutating zone, are both relatively large. The radial m.m.f. along the centre-line of the slot in this case is greater than that in any other arrangement in which the same current per layer is divided amongst more than two coil-sides, with the angular slot-pitch unchanged. The transverse and radial m.m.f.'s are respectively obtained from the sum of, and half the difference between, the two currents, as shown in Fig. 5.

From this figure it is clear that the effect of ignoring the radial m.m.f. is not likely to be important in any practical case.

But the radial m.m.f. exists precisely at the time when the displacement of current is very great (see Section 3). The above conclusion may, however, be confirmed analytically as follows.

For the nth harmonic, the magnitude of the current giving the radial m.m.f. is, for one layer,

$$\frac{4}{\pi} I_c \frac{1}{n} \frac{\sin n\beta}{n\beta} [\sin \psi n(n_a - 1) + \sin \psi n(n_a - 3) + \ldots]$$

In this series the last term refers to the $\frac{1}{2}(n_a - 1)$th coil-side if n_a is odd, and to the $\frac{1}{2}n_a$th coil-side if n_a is even.

The summation reduces to

$$\frac{4}{\pi} I_c \frac{1}{n} \frac{\sin n\beta}{n\beta} \left[\frac{\sin \left\{\frac{1}{2}(n_a - 1)\psi n\right\} \sin \left\{\frac{1}{2}(n_a + 1)\psi n\right\}}{\sin \psi n}\right]$$

when n_a is odd; and

$$\frac{4}{\pi} I_c \frac{1}{n} \frac{\sin n\beta}{n\beta} \left[\frac{\sin \left\{\frac{1}{2}n_a \psi n\right\} \sin \left\{\frac{1}{2}n_a \psi n\right\}}{\sin \psi n}\right]$$

when n_a is even.

In practice n_a varies from 1 to 6, and for these values the expression within the brackets above becomes:—

For $n_a = 1$	0
$n_a = 2$	$\sin \psi n$
$n_a = 3$	$\sin 2\psi n$
$n_a = 4$	$\frac{\sin^2 2\psi n}{\sin \psi n}$
$n_a = 5$	$\frac{\sin 2\psi n \sin 3\psi n}{\sin \psi n}$
$n_a = 6$	$\frac{\sin^2 3\psi n}{\sin \psi n}$

* These premises are reproduced in Section (3).

Now with increasing order of harmonic, the transverse m.m.f. of a layer decreases, and the radial m.m.f. acting along the centre-line of a slot increases. The investigation of a large number of cases, ranging over the whole normal design field, has brought to light the following facts:—

The series representing separate heating ratios for the odd harmonics from 1 upwards is extinguished (for practical purposes) at or before the stage at which the centre-line radial m.m.f. for a harmonic becomes equal to the transverse m.m.f. for the same harmonic. It is to be noted that this radial m.m.f. varies from zero at the outer boundary of the limiting conductor to a maximum at the centre-line of the slot; that it acts on a relatively long air path; and that it is only important for harmonics which make but a small contribution to the heating. The conclusion is therefore justified that a method which entirely ignores the effect of the radial m.m.f. is yet a distinct improvement on purely empirical methods.

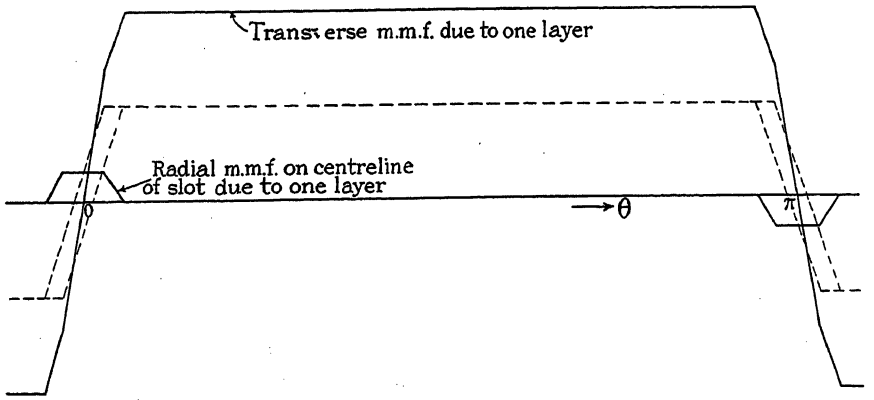


FIG. 5.—Wave-forms of radial and transverse m.m.f.'s due to one layer in one slot, with $n_a = 2$.
18 slots per pole, 2 coil-sides per layer; $2\psi = 5°$, $2\beta = 16°$.

(3) THE DISTRIBUTION OF CURRENT IN THE ARMATURE CONDUCTORS.

When the current of an armature conductor is reversed during the commutating period, the distribution of the current throughout the section of the conductor is changed so that the current is driven towards the mouth of the slot. The end of the period of commutation finds the current non-uniform, and during the interval which elapses before the next commutation the current gradually settles down towards a state of uniform distribution.

The current distribution in conductors which are buried in slots formed in laminated sheet-steel structures was first investigated analytically by A. B. Field.* The following assumptions were made by Field, and by other writers at later dates:—

(1) Rectangular conductors are buried in rectangular slots. (The shape of the slot mouth is immaterial.)

(2) The flux produced by an element of current in a conductor is uniform, normal to the sides of the slot, and is all through or above the element.

(3) The current density along a plane perpendicular to the sides of the slot is constant in one conductor.

(4) The conductor material has uniform resistivity in spite of non-uniform heat production. (The temperature gradients in copper are probably small.)

(5) The reluctance of the magnetic paths through the iron is negligible.

(6) The current distribution is uniform in the end-windings.

Subsequent experience has shown that the discrepancies between test-results and results calculated on the above assumptions are not of engineering importance in alternating-current machines.*

No experimental data are available concerning the losses which occur due to current displacement in direct-current armatures, but Messrs. Lyon, Wayne, and Henderson† have made tests on a model in which current was reversed 120 times per second in a conductor 1 in. deep. The measured current distribution, and that computed after making the assumptions outlined above, were in close agreement.

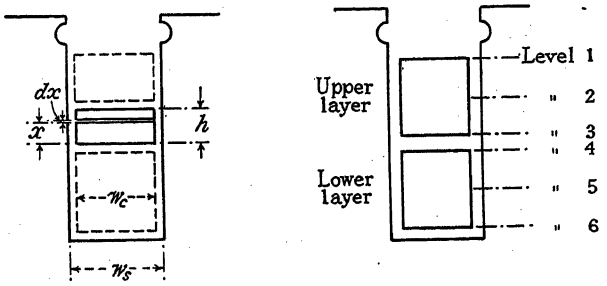


FIG. 6.

The differential equation for the current distribution in a conductor of height h cm, at a level x cm above the bottom of the conductor (see Fig. 6), is

$$\rho\frac{\partial\Delta}{\partial x} - \frac{4\pi}{10^9 w_s}\left[\int_0^x w_c\frac{\partial\Delta}{\partial t}\,dx + \frac{\partial}{\partial t}i_b\right] = 0‡$$

* See Bibliography, (1).

* See Bibliography, (2), (6), (7), (9), (16, discussion), (19), (30), (31), (33).
† *Ibid.*, (41).
‡ This equation is well known, and is developed in several papers. A step-by-step development is given by W. V. Lyon [see Bibliography, (16)].

In this expression, ρ is the resistivity of the conductor material; Δ is the instantaneous current density at the level x; w_s is the width of the slot; w_c is the total width of conducting material in the layer; and i_b is the instantaneous sum of currents in all conductors below the one in question. C.G.S. units are used throughout.

The equation assumes that the currents in the n_a conductors of a layer are in phase, and that the instantaneous value of Δ is the same at all points having the same level.

The solution of this equation is well known for the case in which the current densities are sinusoidal functions in time. In the case of the periodic functions which represent the current in the conductors of a direct-current armature, it is necessary to obtain a Fourier series. This series is solved for each harmonic separately, and the results are added. The results are obtained in a series of fairly rapid convergency.

With regard to the method of solving the above equation for any one harmonic, F. W. Carter* has treated the matter in detail, developing the method from first principles. The author has, however, preferred to use the symbolic treatment due to W. V. Lyon.† This method leads to relatively easy computation, with the aid of Prof. Kennelly's "Tables of Complex Hyperbolic and Circular Functions." In its general application the treatment has the additional advantage that equivalent reactances due to current displacement may be investigated from the same expressions.

In symbolic form, the current density Δ_x at level x, due to a sinusoidal component of amplitude I_1 and frequency f (with current $\mathbf{I}_b$, of the same frequency, flowing in the slot below the conductor in question), is

$$\Delta_x = \frac{\alpha}{w_c}\left[\mathbf{I}_b \sinh \alpha x + \mathbf{I}_1 \frac{\cosh \alpha x}{\sinh \alpha h} - \mathbf{I}_b \cosh \alpha x \tanh \tfrac{1}{2}\alpha h\right]$$

where $\alpha^2 = \dfrac{8\pi^2 f w_c}{10^9 \rho w_s}\sqrt{(-1)}$, or $\alpha = \sqrt{\left[\dfrac{8\pi^2 f w_c}{10^9 \rho w_s}\right]}\underline{/45°}$‡

For a clear deduction of this equation the reader is referred to Item (16) in the Bibliography.

Consider the case of a normal single-turn winding with several conductors side by side in a layer in one slot. It has been shown in Section (2) that for practical purposes the currents in the conductors of a layer may be combined vectorially, and the resultant current used in calculations. (This procedure is equivalent to the replacement of the winding by one having only two conductors per slot, each conductor carrying the resultant current of the layer.) Then, for sinusoidal currents, the expressions for the current density at the top, at the middle, and at the bottom of a layer are:—

$$\text{(Top)} \qquad \Delta_h = \frac{\alpha}{w_c}[\mathbf{I}_1 \coth \alpha h + \mathbf{I}_b \tanh \tfrac{1}{2}\alpha h]$$

$$\text{(Middle)} \qquad \Delta_{\frac{1}{2}h} = \frac{\alpha}{w_c}[\mathbf{I}_1 \tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}\alpha h]$$

$$\text{(Bottom)} \qquad \Delta_0 = \frac{\alpha}{w_c}[\mathbf{I}_1 \operatorname{cosech} \alpha h - \mathbf{I}_b \tanh \tfrac{1}{2}\alpha h]$$

In the special, though quite common, case of a full-pitch single-turn winding, $\mathbf{I}_1$ and $\mathbf{I}_b$ are equal and in phase for the upper layer; and $\mathbf{I}_b$ is zero for the lower layer. Thus at the six levels in the slot representing the top, middle, and bottom of each of the two layers (see Fig. 6), expressions giving the ratio between the actual current density and the nominal current density which would result from uniform distribution are:—

Level (1):—$\alpha h(\coth \alpha h + \tanh \tfrac{1}{2}\alpha h)$
Level (2):—$\alpha h(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}\alpha h)$
Level (3):—$\alpha h(\operatorname{cosech} \alpha h - \tanh \tfrac{1}{2}\alpha h)$
Level (4):—$\alpha h(\coth \alpha h)$
Level (5):—$\alpha h(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}\alpha h)$
Level (6):—$\alpha h(\operatorname{cosech} \alpha h)$

In the above expressions α has the value corresponding to the harmonic under consideration. Thus for the nth harmonic, α is $\sqrt{n}$ times the value of α for the fundamental.

If straight-line commutation is assumed, with a commutating zone of angular width 2β (as in Fig. 2*b*), and with a maximum current $n_a I_c$ in the layer, the nominal current density for the nth harmonic is, in real terms,

$$\frac{4}{\pi}\frac{n_a I_c}{w_c h}\frac{\sin n\beta}{n^2\beta}\sin n\omega t^*$$

Since the harmonic components of the current in the layer are all in phase, the six expressions giving the actual current density in terms of the density $(n_a I_c)/(w_c h)$, and giving their phases relative to that of the harmonics of the nominal current density, are:—

Level (1):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\coth \alpha h + \tanh \tfrac{1}{2}\alpha h)$

Level (2):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}\alpha h)$

Level (3):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\operatorname{cosech} \alpha h - \tanh \tfrac{1}{2}\alpha h)$

Level (4):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\coth \alpha h)$

Level (5):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}\alpha h)$

Level (6):—$\dfrac{4}{\pi}\cdot\dfrac{\sin n\beta}{n^2\beta}\sqrt{nah}(\operatorname{cosech} \alpha h)$

In these expressions (and subsequently) the value of α is that calculated for the fundamental.

* See Bibliography, (40).
† Developed in "Heat Losses in the Conductors of A.C. Machines" [see Bibliography, (16)].
‡ If $|\alpha|$ is the modulus, or numerical value of α, then $|\alpha| = m\sqrt{2}$, where m is the quantity used by A. B. Field. For a copper winding, the expression for $|\alpha|$ reduces to:—

$|\alpha| = 3{\cdot}42\sqrt{\left[\dfrac{fw_c}{w_s(234{\cdot}5+x°\,\mathrm{C})}\right]}$ at $x°$ C; $|\alpha| = 0{\cdot}193\sqrt{\left[\dfrac{fw_c}{w_s}\right]}$ at 80° C.;

$|\alpha| = 0{\cdot}205\sqrt{\left[\dfrac{fw_c}{w_s}\right]}$ at 45° C.; $|\alpha| = 0{\cdot}187\sqrt{\left[\dfrac{fw_c}{w_s}\right]}$ at 100° C.

* In the case of a winding having s turns per coil, the expression is still correct, since the maximum current per layer is $(n_a s I_c)$, and the section of the layer is $(w_c s h)$, where h is the height of the conductor.

An Example of the Current Distribution.

To illustrate the manner in which the current is distributed in the slot windings of a direct-current armature, an example has been completely calculated over one half-period of the fundamental. The case illustrated is that of a full-pitch winding with only one conductor per layer in one slot.

The calculation has been carried out up to, and including, the 21st harmonic, with a value of $|a\hbar|$ equal to 1·5, and a commutating zone of 12° fundamental angular width. These values are fairly representative of modern practice.

The diagrams shown in Fig. 7 demonstrate the values, at the six levels, of the current densities due to individual harmonics. Fig. 7(*a*) refers to the fundamental; 7(*b*) to the fifth harmonic; 7(*c*) to the eleventh; and 7(*d*) to the twenty-first. The densities are shown relative in magnitude to the nominal density $(n_a I_c)/(w_c h)$; the vectors also show their phases relative to the sinusoidal components of the nominal-current-density function, whose vectors would be drawn horizontally towards the right.

The total current density at the six levels, calculated from moment to moment over one half-period of the fundamental, is shown in Fig. 8, relative to the nominal density $(n_a I_c)/(w_c h)$. It is noteworthy that the current does not appear to have settled down until an interval has elapsed corresponding to fully five times the period of commutation.

The method of calculating the vectors in Fig. 7, and the calculation of one point on each of two curves in Fig. 8, are shown in Appendix I.

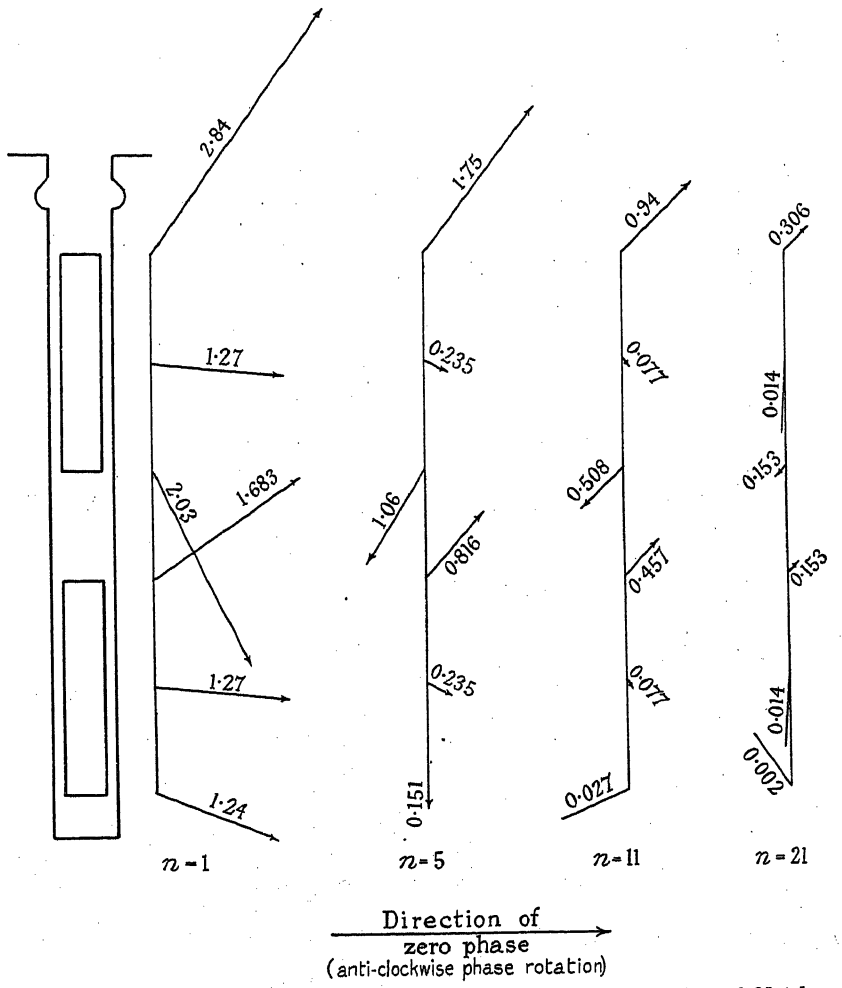


FIG. 7.—Magnitude and phase of the current density due to the 1st, 5th, 11th, and 21st harmonics, at the six levels shown in Fig. 6.

Current wave-form as in Fig. 2(*b*). The figures are amplitudes of current-density components relative to the density $[n_a I_c/(w_c h)]$.

(4) THE METHOD OF CALCULATION OF THE HEAT LOSS.

An expression has been given in Section (3) for the current density at a level x in a conductor, in terms of the conductor dimensions, the quantity α, and the currents $\mathbf{I}_1$ and $\mathbf{I}_b$ in the conductor and below the conductor respectively.

By expressing the loss in an element, and integrating, the loss in one turn of a layer, in a whole layer, or in a whole slot, may be determined.

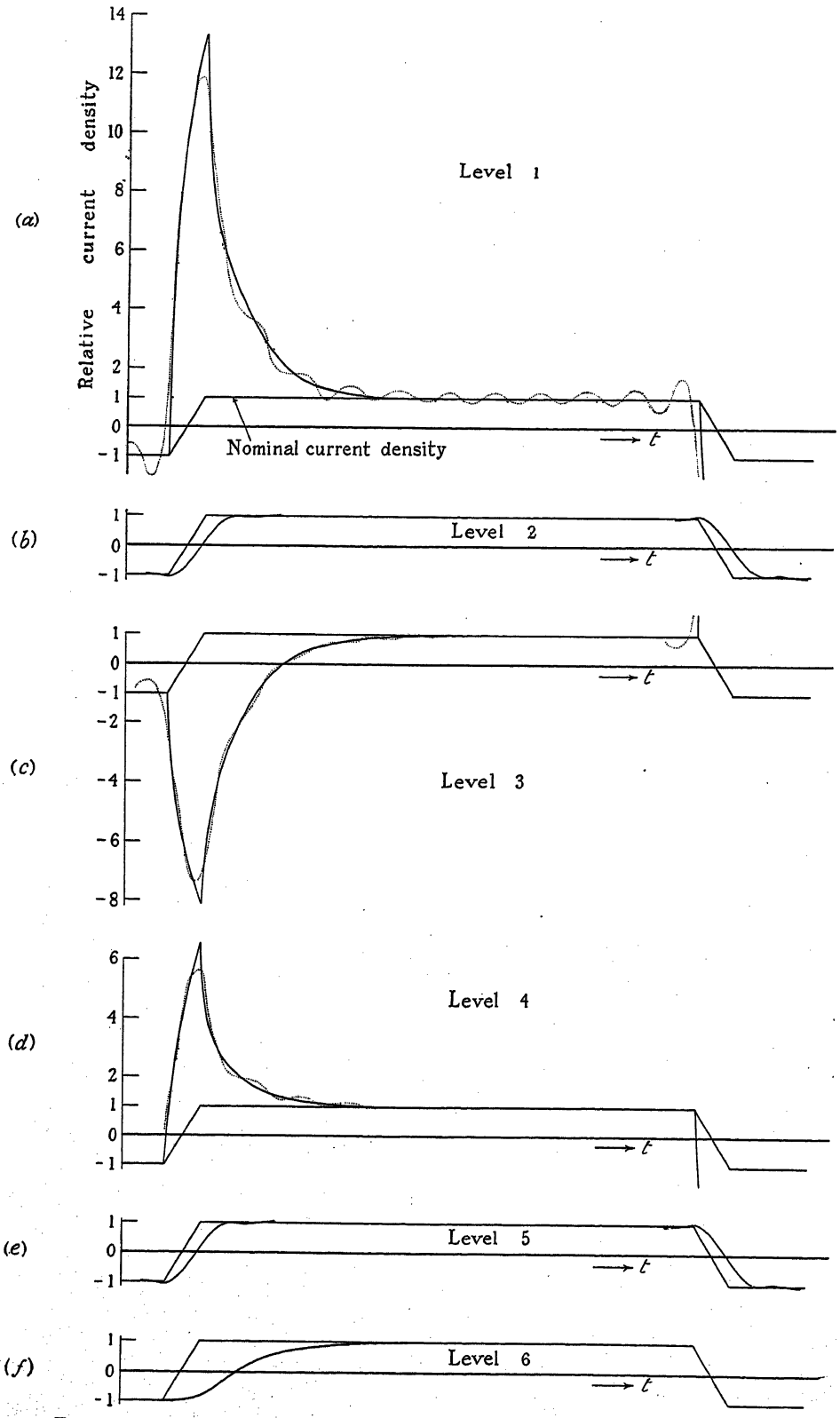


FIG. 8.—Curves of current density against time at different levels in the slot.

The dotted curves of (*a*), (*c*), and (*d*), and the full-line curves of (*b*), (*e*), and (*f*) are as actually calculated. The full-line curves of (*a*), (*c*), and (*d*) are made to correspond as nearly as possible to the values which would be obtained by calculating further members of the series. The position of each level is defined in Fig. 6.

W. V. Lyon* has shown that heating ratios, and reactive power ratios in the various cases can all be expressed as functions of **M** and **N** where

$$\mathbf{M} = ah \coth ah = M_r + jM_x$$
$$\mathbf{N} = 2ah \tanh \tfrac{1}{2}ah = N_r + jN_x$$

In these expressions, M_x and N_x are only needed in calculations of reactive power. Thus in considering the ratio between actual heating and that which would occur with uniform current distribution, the functions M_r and N_r are needed. A table of calculated values of the functions M_r and N_r over a range sufficient to cover practical needs is given in Appendix II.

The windings of direct-current armatures are almost invariably of the two-layer type, with one or more coil-sides side by side in a layer, and one or more conductors per coil-side (or turns per coil). Lamination of the conductors is not resorted to; the mechanical difficulties associated with such a feature in rotating two-layer windings appear to be too great, so that laminated windings are not considered here.

If a sinusoidal current of amplitude I_1 flows in a conductor, and current of amplitude I_b flows in the slot below this conductor with a phase angle ϕ between them, then the ratio of the actual loss to the loss which would occur with uniform current distribution, is K, where

$$K = M_r + \left(\frac{I_b^2}{I_1^2} + \frac{I_b}{I_1}\cos\phi\right)N_r$$

Applying this to standard cases:—

(1) A one-layer-per-slot winding, or the lower layer of a two-layer winding.

$$K = M_r + (p^2 - p)N_r$$

for the pth conductor (counting from the bottom of the layer) and

$$K = M_r + \tfrac{1}{3}(s^2 - 1)N_r$$

for the whole layer in an s-turn winding.

(2) The upper layer of a two-layer winding, with s turns per layer, where all conductors of both layers are of the same size and carry the same current, but where the two layers differ in phase by angle ϕ.

$$K = M_r + \left[p^2 - p + s^2 + (2p - 1)s\cos\phi\right]N_r$$

for the pth conductor; and

$$K = M_r + \left[\tfrac{1}{3}(4s^2 - 1) + s^2\cos\phi\right]N_r$$

for the whole layer.

(3) The average ratio for the slot containing a two-layer winding, the currents in the two layers differing in phase by angle ϕ, is obtained from the cases above, and is

$$K = M_r + \left[\tfrac{1}{3}(5s^2 - 2) + \tfrac{1}{2}s^2\cos\phi\right]N_r$$

These may be applied to two-layer windings, having one, two, or three turns, with all conductors the same size, whether full-pitch or chorded windings. The resultant values of K are given in Table 1.

* See Bibliography, (16), for this, and for the loss-ratio expressions which follow.

TABLE 1.

Values of K in Standard Two-Layer Windings. All Conductors Same Size.

	$\phi \neq 0$	$\phi = 0$
	Single-Turn Windings.	
Slot ..	$M_r + \frac{1}{2}N_r(1 + \cos\phi)$	$M_r + N_r$
Upper layer	$M_r + N_r(1 + \cos\phi)$	$M_r + 2N_r$
Lower layer	M_r	M_r
	Two-Turn Windings.	
Slot ..	$M_r + N_r(3 + 2\cos\phi)$	$M_r + 5N_r$
Upper layer	$M_r + N_r(5 + 4\cos\phi)$	$M_r + 9N_r$
Second turn	$M_r + 6N_r(1 + \cos\phi)$	$M_r + 12N_r$
First turn..	$M_r + N_r(4 + 2\cos\phi)$	$M_r + 6N_s$
Lower layer	$M_r + N_r$	$M_r + N_r$
Second turn	$M_r + 2N_r$	$M_r + 2N_r$
First turn..	M_r	M_r
	Three-Turn Windings.	
Slot ..	$M_r + N_r(\frac{4}{6}\frac{3}{3} + \frac{3}{2}\cos\phi)$	$M_r + \frac{7}{6}\frac{0}{0}N_r$
Upper layer	$M_r + N_r(\frac{3}{3}\frac{5}{3} + 9\cos\phi)$	$M_r + \frac{6}{3}\frac{3}{3}N_r$
Third turn	$M_r + 15N_r(1 + \cos\phi)$	$M_r + 30N_r$
Second turn	$M_r + N_r(11 + 9\cos\phi)$	$M_r + 20N_r$
First turn..	$M_r + N_r(9 + 3\cos\phi)$	$M_r + 12N_r$
Lower layer	$M_r + \frac{8}{3}N_r$	$M_r + \frac{8}{3}N_r$
Third turn	$M_r + 6N_r$	$M_r + 6N_r$
Second turn	$M_r + 2N_r$	$M_r + 2N_r$
First turn..	M_r	M_r

The above expressions are in order even if the conductors are not of the same height in the two layers, so long as the current is the same in magnitude for each layer. But it must be remembered that $|ah|$ is not the same for both layers, whence M_r and N_r will not be the same throughout the slot.

Now the actual loss in a conductor of resistance R ohms, carrying a sinusoidal current of amplitude I_1 amperes, is

$$\tfrac{1}{2}KI_1^2R \text{ watts}$$

If the value of K computed for the nth harmonic of the current of trapezoidal wave-shape is denoted by K_n, then the loss in one layer due to this harmonic is

$$\tfrac{1}{2}K_nR\left[\frac{4}{\pi}(I_c n_a s)\left(\frac{1}{n}\frac{\sin n\beta}{n\beta}\right)\left(\frac{\sin n_a\psi n}{n_a \sin\psi n}\right)\right]^2$$

The expression in the bracket is the resultant nth harmonic current of one layer, if I_c is the maximum value of the current in one conductor (see Section 2).

The simplest method of estimating the loss in a winding due to uniformly distributed current is to obtain the product of the resistance between brushes and the square of the steady direct current. This method forms a convenient basis for the loss ratio of the direct-current armature. On this basis the loss ratio in the buried portion of the winding is, for the nth harmonic,

$$K_n' = \frac{8}{\pi^2}\left(\frac{1}{n}\frac{\sin n\beta}{n\beta}\right)^2\left(\frac{\sin n_a\psi n}{n_a \sin\psi n}\right)^2 K_n$$

where K_n is obtained from Table 1, in terms of M_r and N_r. The value of $|\alpha h|$ used in finding M_r and N_r (see Table 7 in Appendix II) is $\sqrt{n}$ times that calculated for the fundamental.

The heating ratio for the buried winding is given by the sum of the values of K'_n for the various harmonics.

An example illustrating the method is given in Table 2, Section (5).

(5) The Heat Loss in Single-Turn Full-Pitch Windings.

If the two layers, one above the other in a slot, have conductors of equal height, and carry currents which have no phase difference between them, the relevant values of K are given in Table 1. For a full-pitch single-turn winding, K is equal to $(M_r + N_r)$ for the whole slot.

To illustrate the method of calculating the heating ratio of the buried portion of a winding, an example is detailed in Table 2.*

It is clear from Table 2 that the calculation of the heating ratio is laborious. Attempts have therefore been made to reduce the labour involved, by making a very large number of calculations with the object of plotting a standard curve, and determining coefficients for use in conjunction with the standard curve in non-standard cases. Since the heating ratio depends upon $|\alpha h|$, n_a, β, and ψ, it is not possible to plot all the variables continuously. It was decided to investigate three angular widths of commutating zone, viz. 8°, 12° (standard), and 16° (counting the pole-pitch 180°). For each of these values calculations were made over a range of values of $|\alpha h|$ from 1 to 2, and over the usual practical range of values of coil-sides per layer (n_a) and commutating bars per pole.

An armature having 15 slots per pole and 45 commutator segments per pole, with a 12° commutating zone, has been adopted as a standard. The heating ratios for this case are given in Fig. 9.

For fixed values of slots per pole and coil-sides per layer (i.e. fixed values of n_a and ψ), the change in the heating ratio when changing from a commutating zone of 12° to one of 8° or 16° varies slightly with the value of $|\alpha h|$. This latter variation is so slight that mean values, weighted in favour of the commonest values of $|\alpha h|$, viz. 1·4 to 1·6, have been chosen and are given as coefficients in Fig. 11.

Table 2.

Example of Calculation of Slot-Heating Ratio for Buried Windings.†

n	(1) $\frac{1}{n}\cdot\frac{\sin n\beta}{n\beta}$	(2) $\frac{\sin n_a\psi n}{n_a \sin \psi n}$	(3) $[(1)\times(2)]^2$	(4) $\lvert\alpha h\rvert_n$	(5) $[M_r + N_r]_n$	(6) $\frac{K'_n}{8/\pi^2}$
1	0·998	0·999	0·995	1·56	1·6	1·591
3	0·328	0·988	0·105	2·7	4·75	0·499
5	0·191	0·966	0·0341	3·49	7·35	0·250
7	0·1304	0·934	0·0148	4·13	9·3	0·138
9	0·0953	0·891	0·0072	4·69	10·6	0·077
11	0·072	0·839	0·0036	5·18	11·5	0·042
13	0·0553	0·777	0·0019	5·63	12·4	0·023
15	0·0425	0·707	0·0009	6·05	13·18	0·012
17	0·0323	0·629	0·0004	6·44	13·9	0·006
19	0·0242	0·545	0·00017	6·81	14·6	0·003
21	0·0175	0·454	0·00006	7·16	15·28	0·001
					Total ..	2·64

Heating ratio for slot $= K_0 = 2{\cdot}64 \times 8/\pi^2 =$ 2·14

The change in the heating ratio K_0, made by a given change in the values of n_a or ψ, is also small, and varies over the practical range between + 6 per cent and − 8 per cent approximately. Here again the change depends slightly on the value of $|\alpha h|$, and mean values, weighted in favour of the commonest values of $|\alpha h|$, have been chosen and are given as coefficients in Fig. 10.

A selection of the values of K_0 which have been calculated for full-pitch single-turn windings is given in Appendix III. It should be noted that these values do not appear in Figs. 9, 10, and 11. They are given to afford information of the extent to which the mean values adopted as coefficients in Figs. 10 and 11 are in error.

By the use of Figs. 9, 10, and 11, it is possible to find K_0, for any ordinary case, within 2 per cent of the computed value. In the more usual cases the error is generally much less than this. Two examples of the use of these curves are given below.

Whilst there is apparently no justification for highly accurate computations according to this method, since

* Reference should be made to the expression for K'_n at the end of Section (4).

† 15 slots per pole; 30 commutator segments per pole; 25 cycles; commutating zone 1/15th of pole-pitch; full-pitch single-turn winding. $h = 1{\cdot}9$ cm; $w_c/w_s = 0{\cdot}72$; $|\alpha| = 0{\cdot}193\sqrt{[25\times 0{\cdot}72]}$; hence $|\alpha h| = 1{\cdot}56$; $n_a = 2$; $2\psi = 6°$; $2\beta = 12°$.

the divergence from the truth may be appreciable, it is felt that the graphs of coefficients in Figs 10 and 11 are justifiable, on the ground that comparisons between alternative designs are possible. The degree of accuracy in comparison is probably very high relative to the degree of accuracy in absolute predetermination.

Examples of the Use of Figs. 9, 10, 11.

The buried winding investigated in Table 2 has a loss ratio of 2·14. To find the loss ratio from the curves in Figs. 9, 10, and 11, it is necessary to find a ratio from Fig. 9 and to multiply it by coefficients found from Figs. 10 and 11. Thus for $|\alpha h| = 1{\cdot}56$ the heating ratio $= 2{\cdot}112 \times 1{\cdot}014 \times 1 = 2{\cdot}14$.

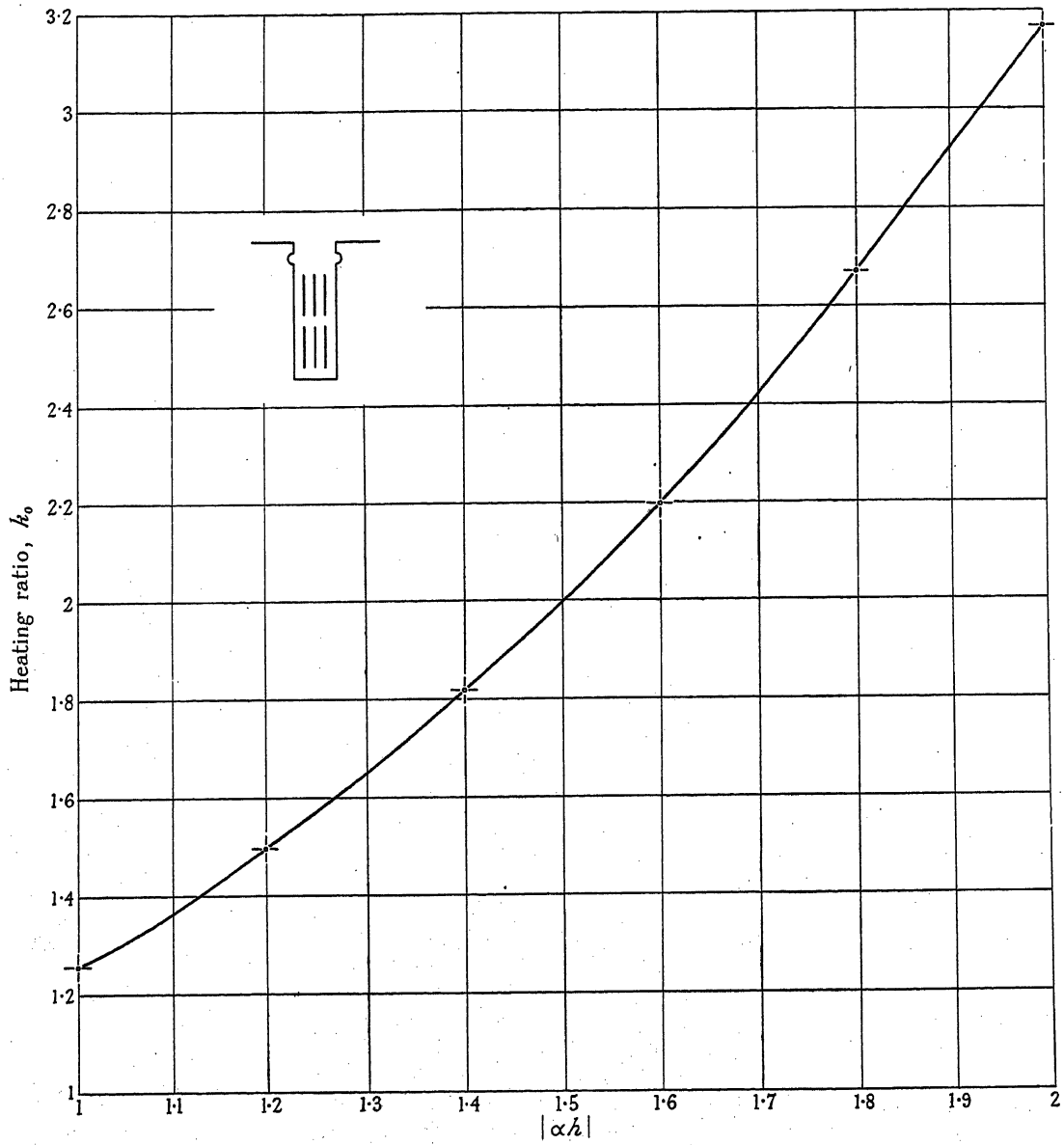


FIG. 9.—Heating ratio for the buried portion of the standard winding.

This curve applies to a full-pitch single-turn winding with 15 slots per pole, 3 coil-sides per layer, and a commutating zone 1/15th of the pole-pitch in width. For windings which differ from this, if still full-pitch and single-turn, multiply ratio by coefficients from Figs. 10 and 11.

$$|\alpha| = \sqrt{[8\pi^2 f w_c/(10^9 \rho w_s)]}$$

For copper $|\alpha| = a\sqrt{[f w_c/w_s]}$

where $a = 0{\cdot}193$ at 80° C.
$= 0{\cdot}187$ at 100° C.
$= 8{\cdot}42/\sqrt{(234{\cdot}5 + x^\circ \text{ C.})}$ at x° C.

As a further example, suppose it is desired to investigate a full-pitch single-turn winding having 12 slots per pole and 60 commutator bars per pole. Suppose the angular width of the commutating zone is 10°, and that $|\alpha h| = 1{\cdot}6$. Fig. 9 gives a ratio 2·198 for $|\alpha h| = 1{\cdot}6$; Fig. 10 gives 0·972; Fig. 11 gives, as an approximate

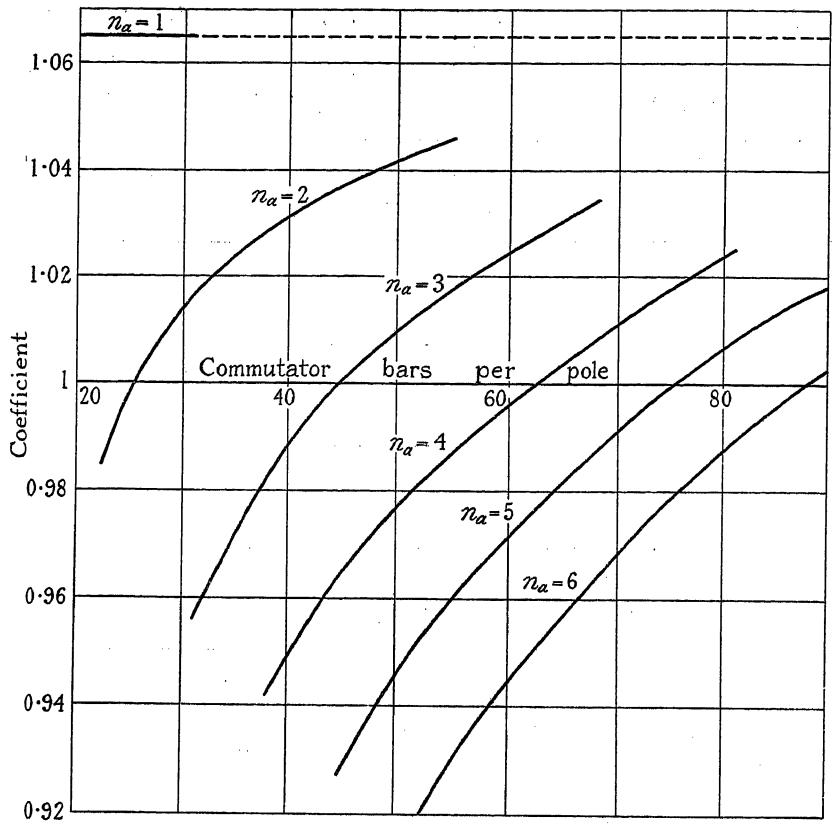


FIG. 10.—Coefficients to cover a change of n_a and commutator bars per pole from the standard of $n_a = 3$, and 45 bars per pole, i.e. 15 slots per pole.

Curves calculated for 12° commutating zone. For other zones multiply coefficient by one obtained with the aid of Fig. 11.

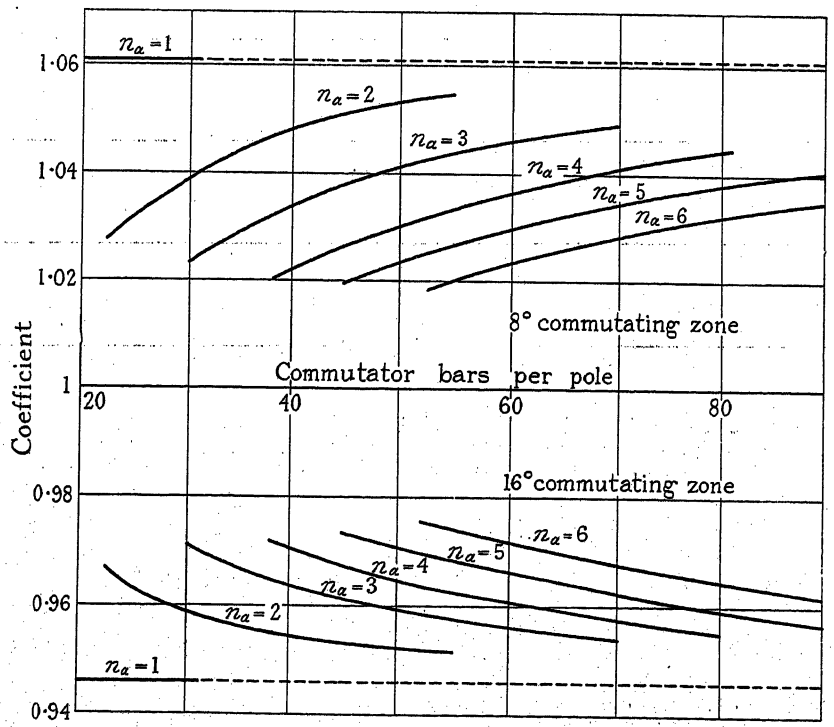


FIG. 11.—Coefficients to cover a change of commutating zone from the standard of 12°, to 8° and 16°.

interpolation, 1·015. The required ratio is thus 2·198 × 0·972 × 1·015 = 2·17. Detailed computation gives 2·16.

The Unequal Heating of Upper and Lower Layers in Single-Turn Windings.

As shown in Section (4), the heating of the lower layer of a single-turn winding depends on the function M_r, and that of the upper layer (if the winding has full-pitch) on the function $(M_r + 2N_r)$. The ratios already given are for mean slot heating, which depends on the function $(M_r + N_r)$, when all the conductors have the same size and carry the same current.

In any given case the calculations may be repeated, using values of the new functions, to obtain heating ratios for the two layers separately. This has been carried out for the standard case (15 slots per pole, 45 commutator bars per pole, commutating zone 1/15th of the pole-pitch), over the range $|ah| = 1$ to $|ah| = 2$, and a graph of the results is given in Fig. 12.

The graph shows that heating in the upper layer may

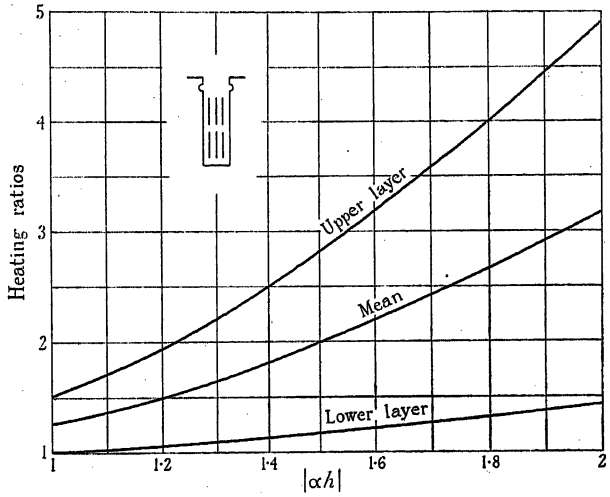


FIG. 12.—Heating ratios for the two layers separately, in the standard full-pitch single-turn winding.

Ratios calculated for a full-pitch single-turn winding, with 15 slots per pole, 3 coil-sides per layer, and a commutating zone 1/15th of the pole-pitch in width. The ratios differ slightly with differences in windings.

be severe, whilst that in the lower layer is never very much higher than that for uniform current distribution.

(6) The Heat Loss in Two-Turn Full-Pitch Windings.

The standard armature with 15 slots per pole, 45 commutator bars per pole, and a commutating zone of 1/15th of the pole-pitch, has been investigated for two-turn windings, over a range of $|ah| = 0·6$ to $|ah| = 1·2$. The results are given in Fig. 13, for each turn, for each layer, and for the whole slot.

The heating ratio for the top turn in the slot is high, and the extra heating for the whole of the buried winding is by no means negligible.

It will be observed that the heating ratios tend to values which fall below unity as $|ah|$ decreases. This depends on two causes. Firstly, a trapezoidal current wave is being calculated in terms of a uniformly distributed current of rectangular wave-form; thus, in the entire absence of any current displacement, the heating ratio would be $\left[1 - \frac{2}{3}(2\beta/\pi)\right]$, which is 0·9735, 0·9556, and 0·9408 for $2\beta = 8°$, 12°, 16° respectively. Secondly, the radial m.m.f. current component has been ignored; the heating due to this component is unknown, but in this treatment even the nominal loss due to it is omitted. The precise effect of the second cause is ascertainable in

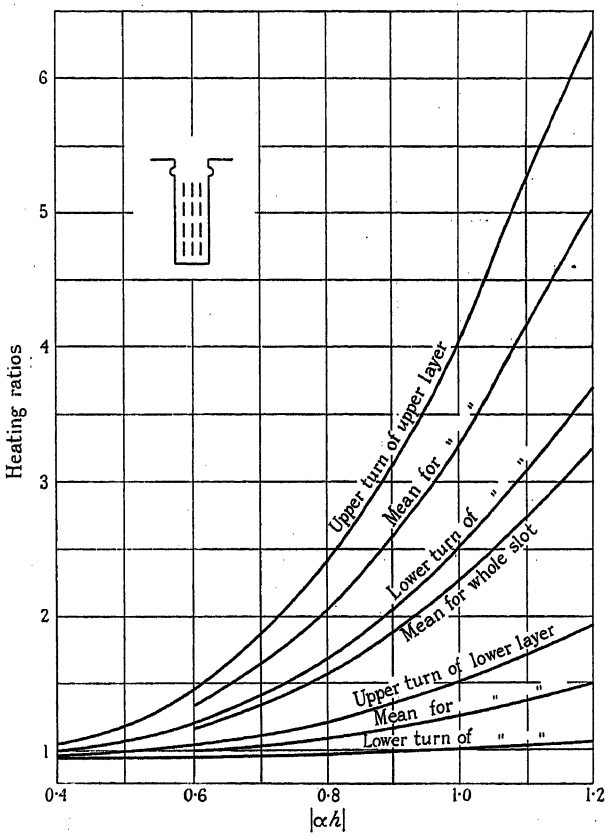


FIG. 13.—Heating ratios for the turns and layers separately, in the standard full-pitch two-turn winding.

Heating ratios for buried windings, calculated for a full-pitch 2-turn winding, with 15 slots per pole, 3 coil-sides per layer, and a commutating zone 1/15th of the pole-pitch in width. The ratios differ slightly with differences in windings.

any given case by repeating the calculation with only one coil-side per layer. This latter calculation in any case gives the maximum value of the heating ratio, and the true ratio must lie between the computed one and the maximum. That the maximum possible error is never more than a small one may be inferred from a study of Fig. 10.

The curve for the heating in the top turn shows a point of inflection, which is really a faint echo of the inflexion in the curve of the function N_r, since the former curve is a function of $(M_r + 12N_r)$.

(7) The Heat Loss in Three-Turn Full-Pitch Windings.

The armature which has been adopted as standard has again been investigated for three-turn full-pitch windings, over a range of $|ah| = 0·4$ to $|ah| = 0·7$. The

results are given in Fig. 14, for the top turn, for each layer, and for the whole slot.

Again the heating ratio for the top turn is high, and the extra heating for the whole of the buried winding is in no practical case negligible.

Single-, Two-, and Three-Turn Windings Compared.

If comparisons are made between single-, two-, and three-turn windings, with the same *total* depth of conducting material in the slot, there is certainly less extra loss the more the number of turns, over the practical range of $|\alpha h|$. The *extra* loss is very roughly inversely proportional to the number of turns.*

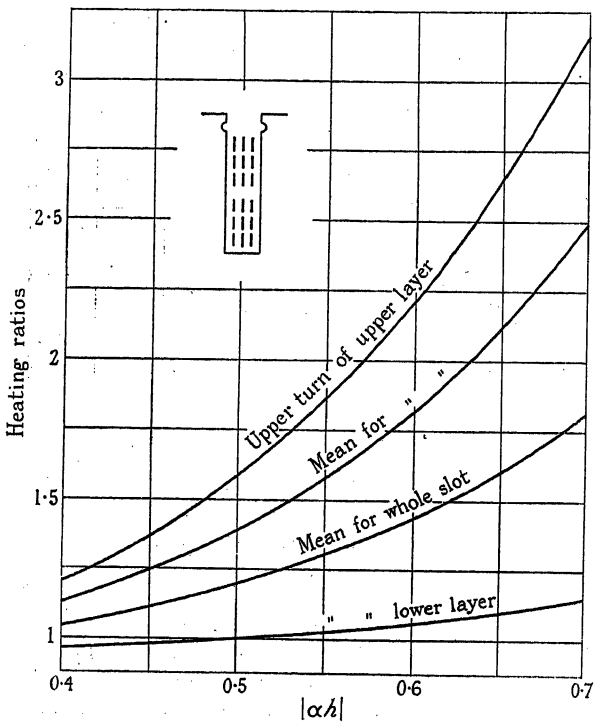


FIG. 14.—Heating ratios for the topmost turn and the two layers separately, in the standard full-pitch 3-turn winding.

Heating ratios for buried windings, calculated for a full-pitch 3-turn winding with 15 slots per pole, 3 coil-sides per layer, and a commutating zone 1/15th of the pole pitch in width. The ratios differ slightly with differences in windings.

(8) THE HEAT LOSS IN CHORDED WINDINGS.

The effect of chording a winding is to reduce the amount of extra heating due to current displacement. It will be seen from the expressions given in Section (4) that a difference in phase between two layers in a slot does not affect the heating of the lower layer, but reduces that of the upper layer.

Calculations have been made in the case of the standard armature with a single-turn winding, assuming three degrees of chording, viz. ½-slot, 1-slot, and 1½-slot chording. It is hoped that the results, which are given in Fig. 15, will afford some guide as to the effect of chording in the general case. The results are given in the form of percentage reductions of the heating ratio, in terms of the corresponding full-pitch winding.

(9) MINIMUM LOSS AND MINIMUM TEMPERATURE-RISE IN DIRECT-CURRENT WINDINGS.

Minimum Loss.

It is well known that in the case of windings which carry a sinusoidal current there is in every case a value of $|\alpha h|$ which results in the minimum loss in the buried portion of the winding. Thus if $|\alpha|$ is kept constant, and the height of the conductors is varied, there is a "critical conductor height" resulting in the minimum loss. Greater values of conductor height result in smaller nominal current densities, but disproportionately greater loss due to current displacement. The same phenomenon occurs in the windings of direct-current armatures.

If a direct-current armature winding is assumed to carry a given current, and the loss in the buried portion of the winding is investigated over a range of values of $|\alpha h|$, the minimum loss occurs when K_0/h is a minimum.* Assuming that $|\alpha|$ is not varied, the minimum loss occurs when $K_0/|\alpha h|$ is a minimum. In the case of the standard full-pitch single-turn winding (see Fig. 9) this occurs when $|\alpha h|$ is approximately equal to 1·1.

A more useful criterion, however, is the total loss. Assuming that the current displacement in the end windings is negligible, then for a ratio l_1/l of total length of winding to length of buried portion, the minimum total loss occurs when $\left[\left(\frac{l_1}{l}-1\right)+K_0\right]\Big/|\alpha h|$ is a minimum. The results given in Fig. 9 for the standard full-pitch single-turn winding have been used to find the value of $|\alpha h|$ corresponding to minimum loss, for various values of l_1/l. Fig. 16 shows the relation between the ratio l_1/l and the value of $|\alpha h|$ which gives minimum total loss. It should be observed that in all cases the "critical" value of $|\alpha h|$ is not very critical; a variation up to, say, 10 per cent does not, in general, increase the loss by more than a very small amount. Thus if l_1/l is 2·5, the minimum total loss occurs at $|\alpha h| = 1{\cdot}7$; at $|\alpha h| = 1{\cdot}5$ or 1·95 the total loss is only 1 per cent more than the minimum; at $|\alpha h| = 1{\cdot}2$ the total loss is 8 per cent more than the minimum, whilst the buried loss has almost its minimum value.

The data given in Figs. 12, 13, and 14 may similarly be used to find the condition for minimum buried loss or minimum total loss in the whole winding, or the upper layer, or the upper turn of the upper layer, in single-turn, two-turn, or three-turn windings.

In general, the most usual values of $|\alpha h|$ for modern direct-current machines are greater than those which give minimum *buried* loss, particularly in the windings near the mouths of the slots. The usual values of $|\alpha h|$ tend to be such that the total loss is not much greater than the minimum.

* On the basis of the above comparisons, it may be observed that the curves for mean heating in the slot tend to converge at high values of $|\alpha h|$. It can be shown that at values much above the normal practical limit, the single-turn arrangement actually gives *least* heating. The same phenomenon can, of course, be shown in the case of the alternating-current machine.

* The actual loss in one slot is $2K_0I_c^2n_c^2s_0l/(w_ch)$, where K_0 is the loss ratio for the slot, and l is the active length.

Minimum Temperature-Rise.

Just as there is a critical height of conductor for every winding, there is a height which gives a minimum temperature-rise in the buried winding. There is, in general, no connection between the two, and the height which corresponds to minimum temperature-rise is difficult to determine owing to uncertainty regarding the heat paths. The following approximations are put forward for what they are worth.

Assuming that all heat passes through the sides of a coil, and none through the top and the bottom and the ends, the temperature-rise is proportional to the watts dissipated per unit area of these surfaces, i.e. to K_0/h^2. If, in a given design, h is varied, the minimum temperature-rise occurs when $K_0/|\alpha h|^2$ is a minimum. In the case of the standard full-pitch single-turn winding this occurs at a high value of $|\alpha h|$ somewhat beyond the limit of the curve ($|\alpha h| = 2$). If an attempt is made to allow for other heat paths, it is probable that end conduction is roughly proportional to K_0 and so will have little effect on the optimum point; and the top and bottom paths can be approximately allowed for in a given normal case by adding a constant allowance. It is found that in this case the optimum value of $|\alpha h|$ is slightly less than that calculated on the first assumption, and appears to be in the neighbourhood of $|\alpha h| = 1 \cdot 8$ to 2 (depending on the allowance made for top and bottom heat paths, i.e. on the width of conductor material in the slot). Whilst it is clear that an appreciable variation of $|\alpha h|$ from the optimum value would not increase the temperature-rise to a marked degree, it is probable that an investigation based on more complete knowledge of the problem would result in theoretical optimum values corresponding to the usual practical values of $|\alpha h|$.*

(10) The Use of Unequal Sections in the Conductors of the Upper and Lower Layers.

It is not practicable to use different heights of conductor in the two layers of multi-turn windings. In single-turn windings, however, there are two methods of arranging this:—

(1) A bar of the larger section is used, and the active portion of the upper layer of each coil is milled to a smaller height. This method results in a large section in the end-connections.

(2) Each coil is jointed at the end remote from the commutator, the two halves of the coil having different conductor heights. This method allows fractional-slot chording, but increases the heating in one half of the end-windings.

Whichever method is used, the heat produced in the space available for conductor material within the slot is

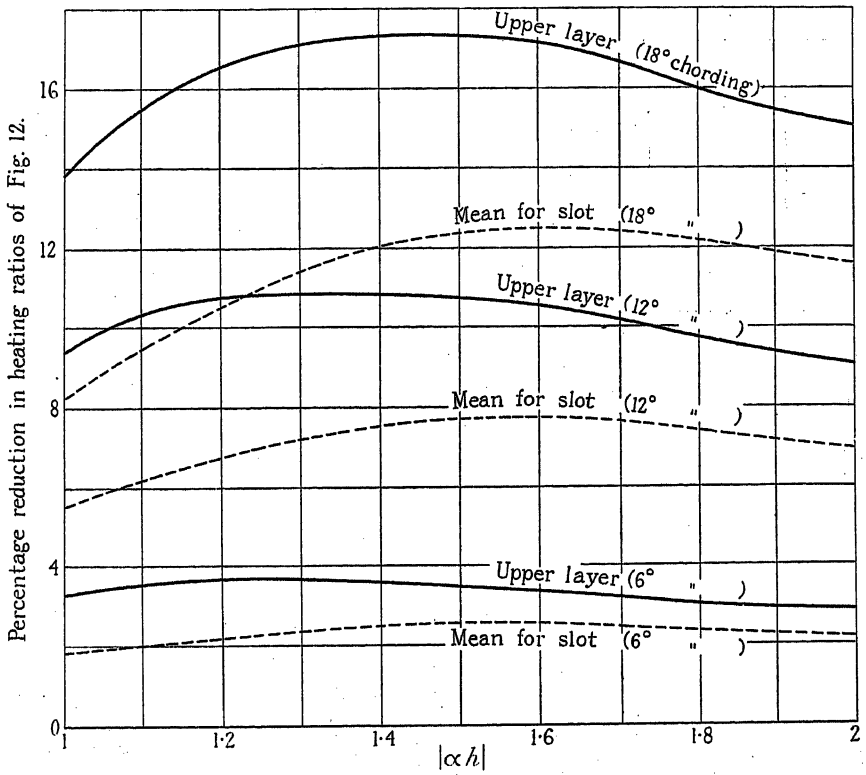


Fig. 15.—Effect of chording the standard single-turn winding by ½, 1, and 1½ slots, in terms of the corresponding full-pitch winding.

Effect of chording the standard single-turn winding (15 slots per pole, 3 coil-sides per payer, commutating zone 1/15th of the pole-pitch in width). Upper layer heating reduced; lower layer not affected.

* An analysis of a number of modern machines with single-turn windings reveals that the value of $|\alpha h|$ is usually in the neighbourhood of 1·5 to 1·6. There are, however, a few examples of values up to 2.

reduced by using a small conductor height for the upper layer, and a large one for the lower layer.

If various arrangements are tried in a fixed available space, it is found that the total heat produced in the slot is gradually reduced as the height of the lower layer is increased at the expense of the upper layer. This is illustrated by the example worked out in Table 3; the case chosen is a full-pitch single-turn winding with two conductors per slot, each conductor being initially 1·9 cm high, with $|\alpha h| = 1{\cdot}6$. The heights are varied, keeping the height of both layers together at 3·8 cm; that is, the mean value of $|\alpha h|$ remains at 1·6. Heating ratios are read from Fig. 12; the heating relative to the nominal I_c^2R loss in a conductor 1·9 cm high is obtained by multiplying each heating ratio by (1·9 ÷ new height). All heating ratios are given to two figures.

If it is assumed that, instead of a reduction in heating, the rating is increased so as to keep the total buried heating loss constant, the effect of varying the conductor heights is shown in Table 4.

TABLE 3.

Effect on the Heating of Variation in Height of Layers, the Total Height being kept Constant at 3·8 cm.

Lower layer				Upper layer				Mean relative heating
Depth	$\lvert\alpha h\rvert$	Heating ratio	Relative heating*	Depth	$\lvert\alpha h\rvert$	Heating ratio	Relative heating*	
cm				cm				
1·9	1·6	1·22	1·22	1·9	1·6	3·18	3·18	2·20
2·0	1·685	1·26	1·20	1·8	1·515	2·88	3·04	2·12
2·1	1·769	1·3	1·18	1·7	1·431	2·60	2·91	2·04
2·2	1·853	1·35	1·17	1·6	1·348	2·33	2·77	1·97
2·3	1·938	1·41	1·16	1·5	1·263	2·10	2·66	1·91
2·4	2·021	1·45	1·15	1·4	1·179	1·89	2·57	1·86
2·5	2·105	1·5	1·14	1·3	1·094	1·70	2·49	1·81
2·6	2·188	1·55	1·13	1·2	1·01	1·53	2·42	1·77

* Relative heating = heating ratio × (1·9 ÷ new height).

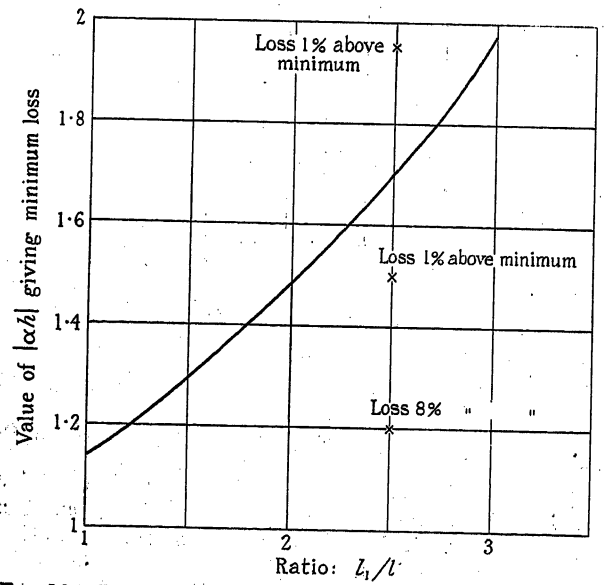


FIG. 16.—Relation between l_1/l (total length ÷ active length) and the value of $|\alpha h|$ which gives the minimum total loss. Based on the standard full-pitch single-turn winding (see Fig. 9).

There is normally a considerable disparity between the heat produced per unit height of conductor in the two layers. Table 4 shows that this disparity is increased when the conductor space is re-divided in an attempt to increase the rating. It is clear that an increase in temperature-rise is inevitable in the upper layer, except in so far as heat can flow to the cooler lower layer, or out to the end-connections. It is therefore essential to investigate the conditions in the end connections.

TABLE 4.

Effect on the Rating of Variation in Height of Layers, the Total Height being kept Constant at 3·8 cm, and the Total Buried Loss being also Constant.

Distance of division between layers above normal position	Lower layer		Upper layer		Rating
	Depth	Relative heating	Depth	Relative heating	
mm	cm		cm		
0	1·9	1·22	1·9	3·18	1·0
1	2·0	1·24	1·8	3·15	1·018
2	2·1	1·26	1·7	3·11	1·035
3	2·2	1·30	1·6	3·08	1·055
4	2·3	1·33	1·5	3·06	1·07
5	2·4	1·36	1·4	3·03	1·085
6	2·5	1·38	1·3	3·01	1·1
7	2·6	1·4	1·2	3·0	1·11

The above case has been investigated in regard to the end connections, but details are not given here. The following facts emerge, assuming constant total buried loss:—

(1) The method which involves the use of bars of large

section, milled down in part, enables the rating to be increased, whilst the total loss actually decreases slightly. The low current densities in the end windings facilitate the flow of heat from the buried windings. The *extra* weight of conductor material needed for a given winding is relatively greater than the increased rating obtainable, in practical cases.

(2) The method involving the use of end connections of the same section as the bars in the slots results in higher current densities in the windings connected to the upper layer. This restricts the flow of heat from the slots, and may, unless the end windings are normally very cool, reduce or nullify the possible increase in rating. The total loss is increased almost to the same extent as the rating, i.e. the loss in the end windings is considerably increased.

It would appear that, apart from the question of cost, the use of different conductor heights in the two layers and the end windings (by butt-welding of bars) is necessary in order to secure maximum rating and maximum economy of material.*

ACKNOWLEDGMENT.

The author desires to record his indebtedness to Dr. A. E. Clayton, Member. This paper is the outcome of a conversation in which Dr. Clayton suggested the usefulness of such an investigation. He has followed its progress, and has from time to time made a number of valuable suggestions.

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It is believed that the following bibliography is fairly complete to the end of 1930.† All the papers, known to the author, which deal with the phenomenon of current displacement in slot-wound conductors at power frequencies, are included. The first and larger section comprises matter which is wholly or mainly concerned with sinusoidal current wave-forms. The second section comprises matter which deals with the problem of the direct-current machine.

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* It is of interest to note that wherever a *reduction* in the height of a conductor would result in a *reduction* of heating loss, the same result would be accomplished by substituting for the conductor one of the *same* dimensions, but of *higher resistivity*.

† Since this paper was submitted, the following references have been found. The author believes that they complete the bibliography up to the end of 1931.

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TABLE 5.

The Magnitude and Phase of each Harmonic of Current Density, relative to the Nominal Density ($n_s I_c / w_c h_s$), and to the Phase of the Harmonics of the Nominal Density. $|\alpha h| = 1{\cdot}5$, $2\beta = 12°$, Full-Pitch Single-Turn Winding (see Figs. 6 and 8).

Order of harmonic	Levels					
	1	2	3	4	5	6
1*	2·837 /54° 7′	1·268 \5° 21′	2·031 \63° 48′	1·684 /33° 18′		1·237 \21° 15′
3	2·195 /54° 59′	0·411 \16° 1′	1·387 74° 26′/	1·039 /46° 29′		0·338 \59° 30′
5*	1·748 /51° 20′	0·233 \26° 28′	1·057 57° 23′/	0·816 /45° 59′		0·151 89° 4′/
7	1·401 /46° 18′	0·153 \36° 30′	0·815 48° 56′/	0·663 /45° 16′		0·080 64° 24′/
9	1·141 /44° 55′	0·107 \46° 5′	0·639 44° 21′/	0·548 /45°		0·045 42° 41′/
11*	0·939 /44° 20′	0·077 \55° 9′	0·508 42° 41′/	0·457 /44° 56′	As for Level 2	0·027 23° 24′/
13	0·775 /44° 11′	0·055 \63° 47′	0·408 42°/	0·381 /44° 56′		0·017 5° 52′/
15	0·635 /44° 13′	0·040 \71° 54′	0·327 42° 2′/	0·315 /44° 58′		0·010 10° 21′\
17	0·513 /44° 20′	0·029 \79° 36′	0·260 42° 20′/	0·255 /45°		0·006 25° 34′\
19	0·403 /44° 26′	0·020 \86° 52′	0·202 42° 46′/	0·202 /45°		0·004 39° 54′\
21*	0·306 /44° 33′	0·014 86° 11′/	0·153 43° 17′/	0·153 /45°		0·002 53° 29′\

* For each of these harmonics, and for the six levels, the values in Table 5 are illustrated in Fig. 7.

Note.—The above angles are all $< 90°$, the appropriate quadrant being indicated in each case.

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APPENDIX I.

THE DERIVATION OF FIGS. 7 AND 8 (ILLUSTRATED BY ONE POINT ON EACH OF TWO CURVES).

The actual current densities at the six levels in the slot (Fig. 6), in terms of the nominal density $(n_a s I_c)/(w_c h s)$, and giving the phase relative to that of the harmonics of the nominal current density, are (see Section 3):—

TABLE 6.

Calculation of Current Density (shown in Fig. 8) for the Instant $\theta = 3°$, for Levels 1 and 6 in Fig. 6. $|ah| = 1{\cdot}5$, $2\beta = 12°$, Full-Pitch Single-Turn Winding.

n	$n\theta$	At level 1			At level 6		
		$(n\theta + \phi_s)$	Sine $(n\theta + \phi_s)$	Density of harmonic	$(n\theta + \phi_s)$	Sine $(n\theta + \phi_s)$	Density of harmonic
1	3°	$/57° 7'$	0·8398	2·383	$\backslash 18° 15'$	− 0·3131	− 0·387
3	9°	$/63° 59'$	0·8987	1·973	$\backslash 50° 30'$	− 0·7716	− 0·261
5	15°	$/66° 20'$	0·9159	1·602	$\backslash 75° 56'$	− 0·9701	− 0·146
7	21°	$/67° 18'$	0·9225	1·292	$85° 24'/$	− 0·9968	− 0·079
9	27°	$/71° 55'$	0·9506	1·084	$69° 41'/$	− 0·9378	− 0·042
11	33°	$/77° 20'$	0·9756	0·916	$56° 24'/$	− 0·8329	− 0·023
13	39°	$/83° 11'$	0·9930	0·770	$44° 52'/$	− 0·7055	− 0·011
15	45°	$/89° 13'$	0·9999	0·635	$34° 39'/$	− 0·5685	− 0·006
17	51°	$84° 40'\backslash$	0·9957	0·511	$25° 26'/$	− 0·4294	− 0·003
19	57°	$78° 34'\backslash$	0·9801	0·396	$17° 6'/$	− 0·2940	− 0·002
21	63°	$72° 27'\backslash$	0·9535	0·291	$9° 31'/$	− 0·1653	—
			Total =	11·853		Total =	− 0·960

Level (1):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\coth ah + \tanh \tfrac{1}{2}ah)$

Level (2):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}ah)$

Level (3):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\operatorname{cosech} ah - \tanh \tfrac{1}{2}ah)$

Level (4):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\coth ah)$

Level (5):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\tfrac{1}{2} \operatorname{cosech} \tfrac{1}{2}ah)$

Level (6):— $\frac{4}{\pi} \cdot \frac{\sin n\beta}{n^2\beta} \sqrt{n}ah(\operatorname{cosech} ah)$

When ah is $1{\cdot}5/45°$ (for the fundamental; and thus $1{\cdot}5\sqrt{n}/45°$ for the nth harmonic), the numerical values of the several terms in the brackets are read from

(37) L. DREYFUS: "The Theory of Extra Commutation Loss in D.C. Machines," *Archiv für Elektrotechnik*, 1915, vol. 3, p. 273.

(38) L. DREYFUS: "Extra Copper Loss due to Current Displacement in Rotary Convertors," *ibid.*, 1915, vol. 4, p. 42.

(39) R. E. GRIME: Discussion on Miles Walker's "Predetermination of the Performance of Dynamo-Electric Machinery," *Journal I.E.E.*, 1915, vol. 54, p. 392.

(40) F. W. CARTER: "Parasitic Current Losses in Bar-Wound D.C. Armatures," *ibid.*, 1927, vol. 65, p. 1002.

(41) W. V. LYON, E. WAYNE, and M. L. HENDERSON: "Heat Losses in D.C. Armature Conductors," *Transactions of the American I.E.E.*, 1928, vol. 47, p. 589.

(42) H. BECHMANN: "Eddy Current Losses in Armature Conductors," *Elektrotechnische Zeitschrift*, 1928, vol. 49, p. 1366.

(43) R. STIX: "Commutation Losses in D.C. Windings," *Archiv für Elektrotechnik*, 1930, vol. 23, p. 593.

Kennelly's "Tables of Complex Hyperbolic and Circular Functions," being obtained in the form $a\angle\theta$. The resultants of the expressions in brackets are obtained in the same form, for each of the eleven harmonics considered. Each value is then multiplied by the appropriate value of $\left(\frac{4}{\pi}\cdot\frac{\sin n\beta}{n^2\beta}\sqrt{nah}\right)$, giving the quantities shown in Table 5.

To compute the current density at any level, and at any instant relative to the instant of zero nominal current density, necessitates the summation of the instantaneous current densities for the various harmonics. Each of these latter is obtained by multiplying the argument given in Table 5 by the sine of the angle $(n\theta + \phi_5)$, where ϕ_5 is taken from Table 5, and θ is the angle representing the chosen instant (see Fig. 8). Table 6 shows the calculation of the current density for the instant $\theta = 3°$ for levels 1 and 6 (see Figs. 6 and 8).

APPENDIX II.

Calculated Values of M_r and N_r.

In Section (4) it is stated that heating ratios and reactive power ratios can be expressed as functions of **M** and **N**, where

$$\mathbf{M} = ah\coth ah = M_r + jM_x$$
$$\mathbf{N} = 2ah\tanh \tfrac{1}{2}ah = N_r + jN_x$$

The coth and tanh functions of so-called "semi-imaginaries" are tabled in Kennelly's "Tables of Complex Hyperbolic and Circular Functions" and from these **M** and **N** may be derived in the form $a\angle\theta$. The real parts of these values are values of M_r and N_r. Table 7

Table 7.

Values of M_r and N_r (see Section 4).

$\lvert ah\rvert$	M_r	N_r	$\lvert ah\rvert$	M_r	N_r
0	1·000	0·000	1·8	1·213	0·790
0·2	1·000	0·000	2	1·310	1·149
0·4	1·001	0·002	3	2·040	3·730
0·6	1·003	0·011	4	2·832	6·100
0·8	1·009	0·034	5	3·528	7·640
1	1·022	0·082	6	4·240	8·820
1·2	1·045	0·169	7	4·950	10·010
1·4	1·085	0·308	8	5·660	11·290
1·6	1·137	0·512			

gives a selection of the values of M_r and N_r (to three places) calculated in making the present investigation.

APPENDIX III.

A Selection of the Values of K_0 Calculated for Full-Pitch Single-Turn Windings.

Some of the values of K_0 which have been calculated for full-pitch single-turn windings are given in Table 8.

Table 8.

Calculated Values of K_0 for Full-Pitch Single-Turn Windings (for Method, see Table 2).

Bars per pole Slots per pole n_a 2ψ		45 22½ 2 4°	30 15 2 6°	22½ 11¼ 2 8°	45 15 3 4°	30 10 3 6°	45 11¼ 4 4°	45 9 5 4°
	$\lvert ah\rvert$							
$2\beta = 8°$	1	1·368	1·315	1·264	1·3	1·226	1·247	1·193
	1·2	1·649	1·582	1·514	1·552	1·461	1·49	1·42
	1·4	1·977	1·901	1·819	1·886	1·751	1·79	1·7
	1·6	2·4	2·313	2·214	2·276	2·138	2·178	2·075
	1·8	2·886	2·785	2·678	2·76	2·588	2·632	2·518
	2	3·42	3·302	3·184	3·268	3·083	3·139	3
$2\beta = 12°$	1	1·303	1·272	1·235	1·256	1·2	1·219	1·175
	1·2	1·561	1·521	1·47	1·496	1·426	1·45	1·392
	1·4	1·87	1·83	1·769	1·819	1·71	1·741	1·668
	1·6	2·283	2·227	2·152	2·198	2·088	2·12	2·036
	1·8	2·76	2·698	2·605	2·67	2·534	2·574	2·47
	2	3·274	3·199	3·107	3·168	3·02	3·07	2·947
$2\beta = 16°$	1	1·247	1·227	1·198	1·213	1·175	1·188	1·15
	1·2	1·489	1·461	1·425	1·44	1·39	1·409	1·36
	1·4	1·789	1·75	1·708	1·741	1·661	1·687	1·625
	1·6	2·178	2·135	2·082	2·107	2·026	2·056	1·984
	1·8	2·633	2·59	2·525	2·572	2·463	2·497	2·413
	2	3·139	3·084	3·012	3·058	2·941	2·98	2·892

Each value has been calculated according to the method demonstrated in Table 2. The calculations were carried out until the terms in the last column of Table 2 dwindled to less than 0·001, this stage being variously reached at from the 13th to the 27th harmonic.

The values of K_0 obtained by using Fig. 9, and the mean coefficients given in Figs. 10 and 11, do not correspond to the calculated values of K_0. The divergence is never great, and a study of these values, in conjunction with results obtained from the curves, will show that the method of adopting mean coefficients is justifiable.

The term "bars per pole" in Table 8 refers to the number of commutator bars or segments between adjacent brush arms.

INSTITUTION NOTES.

Nominations for Election to the Council.

In addition to those members nominated by the Council (see page 143) the following have been nominated for ballot as Ordinary Members of Council:—

A. P. M. FLEMING, C.B.E., M.Sc. [Nominated by B. A. G. Churcher, A. G. Ellis, G. A. Juhlin, H. C. Lamb, H. Pearce, B.Sc.(Eng.), J. S. Peck, J. A. Robertson, Prof. S. Parker Smith, D.Sc., Prof. Miles Walker, D.Sc., F.R.S., and E. B. Wedmore.]

Sir ARNOLD B. GRIDLEY, K.B.E. (Nominated by C. O. Brettelle, Sir James Devonshire, K.B.E., H. Hobson, W. W. Lackie, C.B.E., J. Leggat, Colonel B. C. Lockhart-Jervis, D.S.O., R.E., Colonel T. H. Minshall, D.S.O., R. Nelson, A. M. Sillar, and Johnstone Wright.)

J. W. THOMAS, LL.B., B.Sc.Tech. (Nominated by E. Fawssett, J. Frith, M.Sc., P. B. Hall, T. E. Herbert, A. B. Mallinson, J. H. Parker, G. G. L. Preece, G. F. Sills, H. C. Turner, and J. N. Waite.)

Proceedings of the Wireless Section.

96TH MEETING OF THE WIRELESS SECTION, 24TH FEBRUARY, 1932.

Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 3rd February, 1932, were taken as read and were confirmed and signed.

A general discussion took place on the subject of "The Selectivity of Broadcast Receivers" (see page 103), with an introductory paper (see page 102) by Prof. C. L. Fortescue, O.B.E., M.A.

The meeting terminated at 8.35 p.m. with a vote of thanks to Prof. Fortescue for his introductory remarks, which was moved by the chairman and carried with acclamation.

97TH MEETING OF THE WIRELESS SECTION, 2ND MARCH, 1932.

Mr. L. B. Turner, M.A., Vice-Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 24th February, 1932, were taken as read and were confirmed and signed.

A paper by Mr. H. A. Thomas, M.Sc., Associate Member, entitled "Developments in the Testing of Radio Receivers" (see page 114), was read and discussed.

The meeting terminated at 7.45 p.m. with a vote of thanks to the author, which was moved by the chairman and carried with acclamation.

Elections and Transfers of Members.

At the Ordinary Meeting held on the 17th March, 1932, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Bingham, John Merton.
Booth, Charles Frederick.
Clark, John, B.Sc.
Foster, Joseph Edward.
Smithers, Fred Aubrey.
Sweetlove, James Arthur, B.Sc.Tech.

Companion.

Haslett, Caroline Harriett (Miss), C.B.E.

Associates.

Armstrong, William Thos.
Brack, Herbert Marson.
Branson, James Watson.
Hall, Harold.
Large, Arthur Leslie.
MacKellar, Clifford Edmond, Major, R.A.(T.A.).
Young, James Alexander.

Graduates.

Blackwell, Alfred.
Boag, David James W.
Bray, Victor Henry.
Burch, James Thomas.
Douglas, Archibald Perry, B.E., B.Sc.
Douglas, Thomas Armitage.
Emanuel, Maurice Ranald, B.E., B.Sc.
Evans, Emlyn Rees, B.Sc.
Gale, William Edward J. R. B.
Green, Cecil.
Hammerton, Herbert Reginald.
Hancock, Jeffrey.
Hancox, Leonard John.
Haslewood, Francis Dering.
Jones, Philo Lawton.
Lewis, Norman William J., B.Sc. (Eng.).
Lonsdale, Robert.
Lugg, John Victor.
Marsh, Thomas Eric Eaton.
Perkins, Brian Lea, B.Sc. (Eng.).
Pringle, Robert William.
Probert, Gilbert Ambrose.
Rafi, Mian Mohammad.
Rowe, Alan Henry R.
Stott, Arnold.
Tappin, Launcelot Ponton, M.Sc.

Graduates—continued.

Thomas, Evan David, B.Sc.
Thurston, Albert Peter, D.Sc.
Waine, Ian Leslie.
Wakefield, Kevin Stuart.
Weir, William, B.A.
Whitwam, Thomas Cotton.

Students.

Ananthasayanan, Bangalore Chelvaroya.
Anderson, Ronald Thomas W.
Baguley, Peter William.
Barfield, Reginald Thomas.
Birch, Frederic Henry.
Black, Alexander Colin M.
Braid, Donald Keith.
Burman, Frederick James.
Carr, Arthur Smith, B.Sc.
Christmas, William James.
Cornwell, Wilfrid Dennis.
Drayton-Smith, Edward Eugene.
Elliott, Harry Laurence.
Evans, Reginald John.
Fotheringham, William.
Garbutt, Walter Denis.
Goodwin, James.
Grey, John George.
Gwyther, Hugh Banks.
Hall, Charles Cooper.
Harris, Kenneth Glanfield.
Hey, John Alastair.
Holt, Richard George S.
Ilsley, John Linton.
Jones, Frank.
Kidd, William Leslie.
Kneebone, Henry Claude.
Lavarack, Terence Vaughan.
Limbrey, Geoffrey, Herbert.
Lulla, Pribhasing Sewasing, B.Sc.
McLean, Ronald Ian.
McNeill, William Alexander.
Milne, Archibald George.
Morris, Edward Hollingworth.
Newman, Frank Edward.
Page, Robert Sidney J.
Pearce, Eric Coxeter.
Roberts, Leonard Vickers.
Scharmberg, Albert Joseph.
Scott, Gordon Cameron.
Seconde, Robert Gordon.
Shaw, Clement William.
Shepherd, Frederick Alexander.
Sims, Alfred Edmund J.
Stacey, George Henry F.
Stephenson, Geoffrey Huson.
Stock, Percy Douglas.
Summarsell, Robert.
Suttle, Charles Edward P.
Taylor, Thomas Sidney.
Thomas, Evan James C.
Thomas, John Brynmor.
Thorp, Sidney Derek.
Wainman, Russell Riley.
West, William Clayton.
Whitmore, Scovell Frederick C.
Wood, John Herbert.
Wright, Harry Morrell.
Yates, Richard.

TRANSFERS.

Associate Member to Member.

Bennett, Alfred Harvey.
Campling, Percy George.
Gould, Charles.

Associate to Associate Member.

Bonny, Arthur George A.
Flanagan, Frederick, B.A.
Stobie, James Cyril.

Graduate to Associate Member.

Addison, James Donald.
Beaumont, Frederic Norman, B.Sc.(Eng.).
Cross, Leonard Jack, B.Sc. (Eng.).
Elson, Mayne Bennett, B.A.
Hedley, Isaac Herdman, B.Sc.
Lythgoe, William Herbert L.
Mitchell, Thomas Alfred.
Rhodes, Cecil, M.Eng.
Stoner, Charles Robert, B.Sc.(Eng.).
Young, Reginald Hackworth, B.Sc.(Eng.).

Student to Associate Member.

Clark, John Eric.
Neate, Eric Charles, B.Sc.(Eng.).
Soper, Robert Edwin S., B.Sc.(Eng.).
Tufnail, Maurice Edward.
Tweed, Cyril John F.

In addition, the following transfers have been effected by the Council:—

Associate to Graduate.

Beaglehole, Keith, B.Sc.
Butler, John Henry, M.Sc.
Gray, Charles Marshall.
Slevin, Edward.

Student to Graduate.

Aggarwal, Cyril Frank.
Ainslie, Robert Carlyle.
Anderson, Ian Lind.
Balean, John Herman, B.Sc.(Eng.).
Bird, John Richard, B.Sc.(Eng.).
Bird, William Herbert.
Burgess, Raymond Ernest J., B.Eng.
Campbell, Graham Hamilton.
Chaudhry, Shyam Sarup.
Chubb, William George K.
Cotsworth, Walter Manning.
Creed, John Arnold.
Dadachanji, Phiroze Dinshaw.
Ellis, Robert Henry.
Fyfe, Reginald John, B.Sc.
Gainsford, Guy Bernard.
Gallop, Arthur Hubert, B.Sc.
Ghose, Nirmal Chandra, B.Sc.(Eng.).
Gillespie, John Murray.
Gray, George William.
Hadfield, Bertram Morton, B.Sc.(Eng.).
Hobbs, Norman David.
Hoggan, Leslie Edward A., M.Eng.
Hollman, Cyril Frederick.
Hughes, William.
Ingman, Hemming Eric, B.Sc.(Eng.).
Jewett, Eric.
Jones, Enoch David, B.Sc.
Kapur, Vidya Parkash.
Khandhar, Jagmohandas Popatlal.
Lee, Williamson.
Linton, Arthur Hugh F.
McNeal, George Allan.
Matchett, Miller.
Muir, William Leslie.
Murdoch, Matthew Weir H.
Nicholson, Gordon William.
Page, Harold, B.Sc.
Partridge, Wilfrid Howard.
Patell, Rustom Jehangir, B.E.
Pullar, Ian Douglas.
Ritchie, David Findlay, B.Sc.(Eng.).
Sahgal, Prem Lal.
Sarup, Shanti.
Simpson, George Russell.
Smuts, William Beck.
Thursfield, Donart, B.A.
Titterington, John.
Torrance, Alexander Edward.
Travers-Solly, Thomas Paul.
Vij, Kasturi Lal.
Wainwright, Hector Aitken, B.Eng.
Woodforde, John.

METAL-CLAD SWITCHGEAR, AUTOMATIC PROTECTION, AND REMOTE CONTROL, WITH PARTICULAR REFERENCE TO DEVELOPMENTS DURING THE LAST SEVEN YEARS.

By H. W. CLOTHIER, Member.

(*Paper first received 2nd November, and in final form 19th December,* 1931; *read before* THE INSTITUTION *25th February and 3rd March, before the* TEES-SIDE-SUB-CENTRE *17th February, before the* NORTH-EASTERN CENTRE *22nd February, before the* NORTH-WESTERN CENTRE *23rd February, and before the* DUNDEE SUB-CENTRE *10th March,* 1932.)

SUMMARY.

This paper outlines a picture of the progress during the last seven years in the field it deals with, and also sets out the problems of to-day and the lines of possible future practice. The period under review has seen a change of national policy in Great Britain, which practically puts an end to isolated plants for public service, and enhances the scope for economy by the running of the largest plants with interconnections between them and all other plants and loads. New conditions therefore arise, demanding a reconsideration of the problems dealt with by the author in their earlier form in 1925.

The construction of the various types of metal-clad switchgear is diagrammatically represented by illustrations brought up to date and concluding with a forecast of the full application of the principle of complete enclosure and immersion of all conductors and insulators for all voltages as the means of safeguarding life and property, and securing continuity of supply.

Certain basic constructional features are dealt with more fully. These are, in general, typical of changes, some brought about by research and practical experience, and others evolved in the quest by designers for something "different" in a period of intensified competition. An attempt is made to classify the prevalent forms of arcing contacts and busbar enclosures, and to state the effects of such details, particularly of the latter, on the general lay-out of the whole switching equipment.

The use of metal-clad switchgear has of itself effected such economy in buildings that outdoor switchgear has not been widely used in Great Britain; but reasons are given in favour of outdoor construction.

A review is given of the present position of rating, performance, and selection of circuit breakers, in order to lead up to a better understanding of the interpretation of these terms, and in view of the need for an international agreement on standard conditions for assessing ratings. Results of tests in a British 1 500 000-kVA testing station are recorded as examples.

The need for economy is accepted as a fundamental object for the designer, but it should be effected by the reduction of components rather than by lowering the quality of details. Some ways and means of effecting economy along these lines are therefore proposed.

The automatic isolation of faults has a particular bearing on the protection of property and supply; in the latter its performance in procuring stability is considered to be of paramount importance, and in the former its speed of operation is a criterion of equal merit. In the light of these principles the known protective systems are reviewed, and some new developments are mentioned. This study is in the main a history of the quest of the ideal, which, for the sake of economy alone, excludes the pilot cables of the earlier systems, and thus an opening occurs for the use of telephone pairs. Some original research is recorded for the avoidance of interference with the other uses of such telephone conductors arising from accidents on main lines. Further, the resistance of heavy arcs has been experimentally ascertained, with a view to making clear the necessity of using reactance instead of impedance as the true means of measuring distance for the accurate location and discrimination of faults in the distance types of protection.

The evolution of automatic and remote-control systems is traced from the earlier power-station control-room to the present-day design of regional control from a central room, and the forecast for the future favours the increasing application of mechanical principles, which in the first place tends to avoid errors, and in the second place takes over the responsibility of action in an emergency.

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- (vi) Horizontal or vertical.
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Appendix I. Standard Conditions for Short-Circuit Tests of Circuit Breakers.

Appendix II. Some Short-Circuit Tests of Circuit Breakers.

Appendix III. Reactance versus Impedance Measurements for Distance Relays.

Appendix IV. The Safeguarding of Post-Office Pilots associated with Power Networks.

(1) INTRODUCTION.

In a paper read by the author before the Institution in 1925, an attempt was made to record the then established state of the design of metal-clad enclosure, protective systems, and control, especially in relation to the avoidance of shock and fire, and the maintenance of continuity of supply. It is proposed now to review the present position (thus completing a continuous series* —1902, 1910, 1925, 1932), with particular reference to the developments during the last seven years, under three main headings, namely:—

Switchgear Construction.
Automatic Isolation of Faults.
Remote and Automatic Control.

(2) SWITCHGEAR CONSTRUCTION.

(i) *General.*

An increasing demand, accelerated by the Electricity Act of 1926, has given an impetus to initiative in design. New service conditions have brought about the evolution of units of larger capacity to work at higher

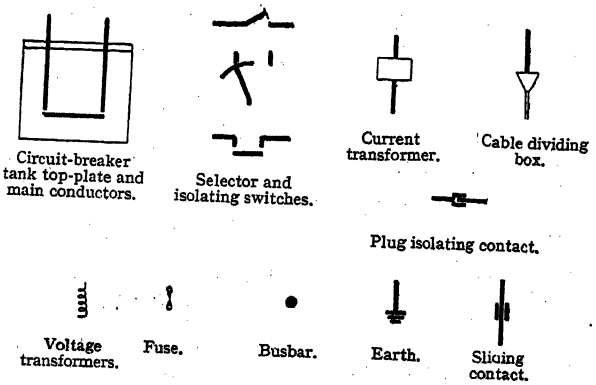


FIG. 1.—Symbols for component parts of diagrams.

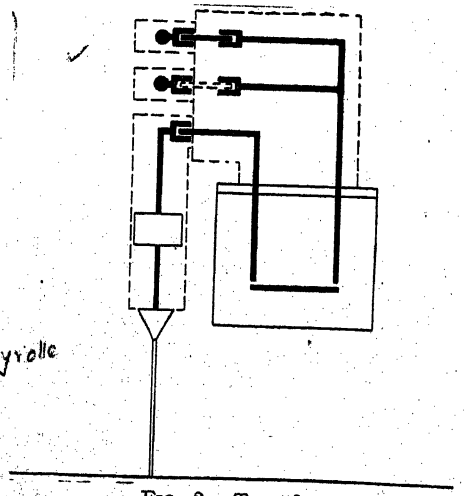


FIG. 2.—Type 1*a*.

In 1925, metal-clad practice was well established in Great Britain; now it is accepted as the normal rule. It is advancing in America, and has obtained a foothold on the Continent.

The need for the avoidance of all chance of the spreading of arcs and consequent fire, leading to possible failures of supply, has brought about an enlarged demand for high quality in constructional details. This

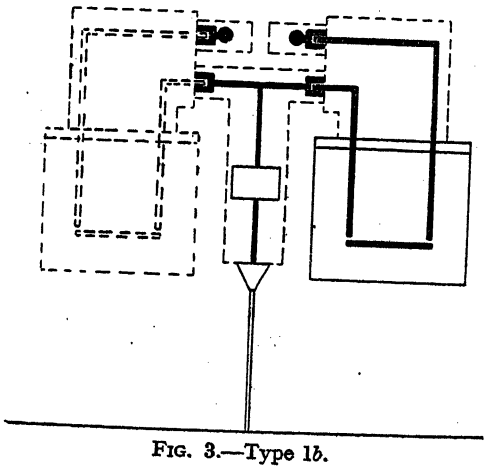


FIG. 3.—Type 1*b*.

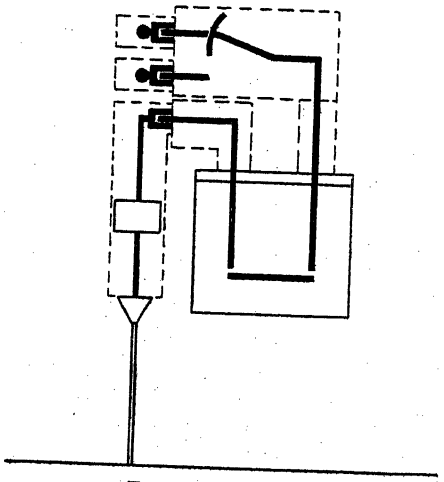


FIG. 4.—Type 1*c*.

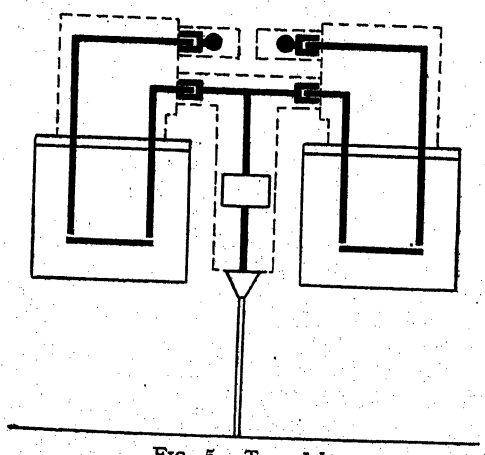


FIG. 5.—Type 1*d*.

* See list of references on page 317.

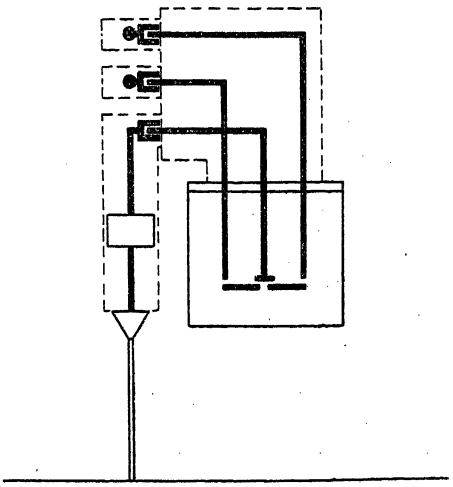


FIG. 6.—Type 1*e*.

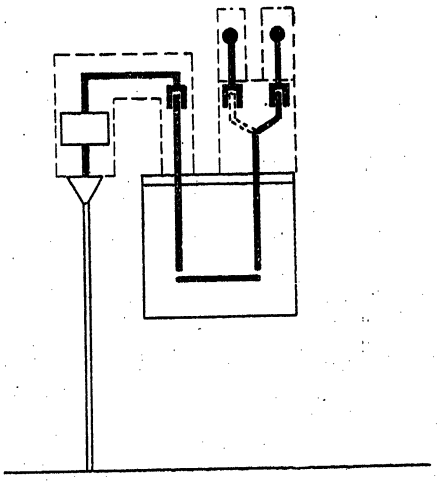


FIG. 7.—Type 2*a* (Railing and Garrard).

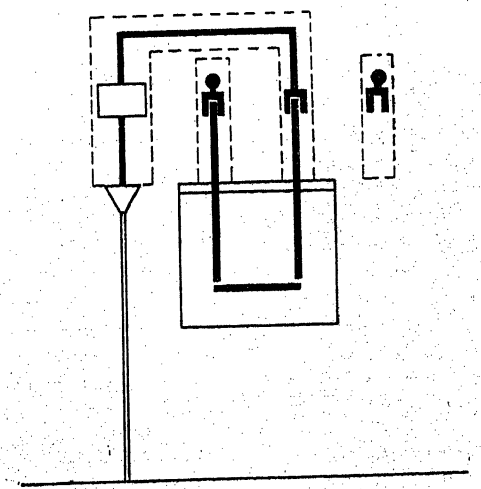


FIG. 8.—Type 2*b*.

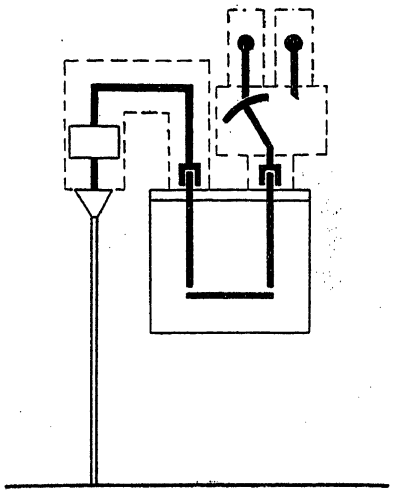


FIG. 9.—Type 2*c*.

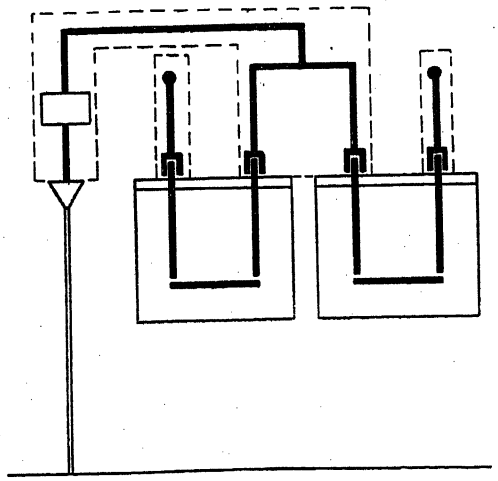


FIG. 10.—Type 2*d*.

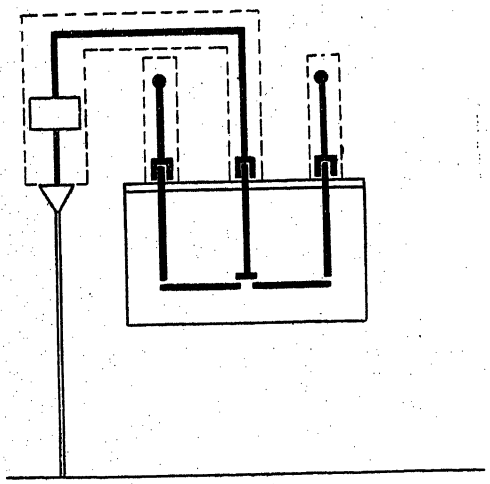


FIG. 11.—Type 2*e* (Ferguson, Pailin Ltd.).

in general has given designers more scope for competition in solidity, and has helped to establish a policy of economy-in-the-long-run in preference to cheeseparing in the initial cost of plant. Economy has been sought in floor space and in housing, rather than in crucial circuit-breaking components.

(ii) Classification.

Figs. 1 to 15 indicate the variety of arrangements, and give a comparative view of the disposition of the main

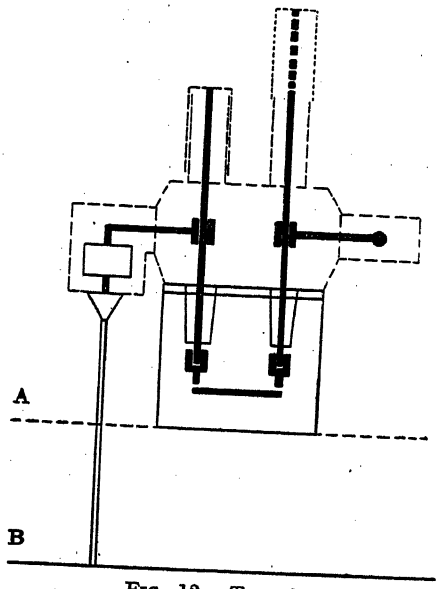


FIG. 12.—Type 3*a*.
A and B.—Alternative floor-levels.

components, namely, busbars (single and duplicate), circuit breakers, current transformers, isolating and selector devices, and cable sealing boxes. The several types of metal-clad switchgear may be divided into three

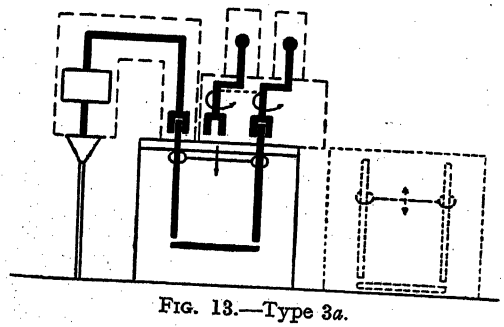


FIG. 13.—Type 3*a*.

generic classes, according to the method of isolation, namely:—

(1) Horizontal draw-out.
(2) Vertical drop-down.
(3) Internal switch and/or internal plug.

Isolation is effected in the first two classes by the drawing-out and the dropping-down respectively of the circuit breaker, but in the third there are separate isolating devices, and the removable portion need only be moved for inspection or maintenance.

These three classes are capable of subdivision into types, according to the method of busbar selection, as follows:—

(*a*) Change-over plugs.
(*b*) Circuit-breaker transference.
(*c*) Change-over switch.
(*d*) Duplicate circuit-breaker.
(*e*) Double-contact circuit-breaker.

(iii) Innovations.

The line diagrams are intended to outline all the varieties of metal-clad switchgear in an elementary way. They are arranged in order of types within the three classes, and it may be useful to point out some of the innovations.

The proposal to use the upward vertical movement of

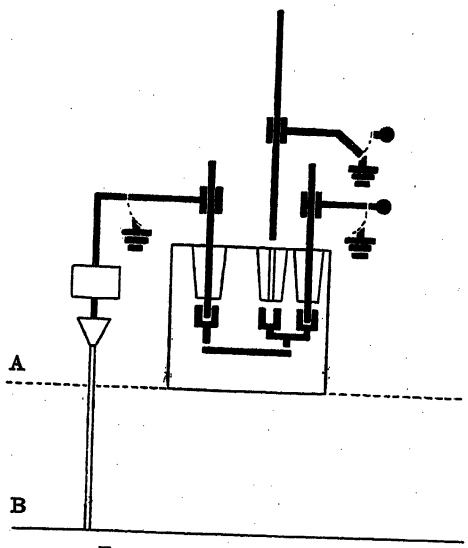


FIG. 14.—Type 3 (*a* and *c*).
A and B.—Alternative floor-levels.

a central fitting for isolating is not new. Its origin was for heavy high-voltage switchgear, in which the circuit breaker was to be stationary* (Fig. 12, Type 3*a*); but it has now been developed in a form† shown diagrammatically in Fig. 13 (Type 3*a*), and in more detail in Fig. 16, wherein the vertical movement is downwards. It has been used in this way for small units in combination with some of the draw-out characteristics of both the horizontal and the vertical metal-clad forms. The circuit breaker itself may rest on the ground and be removed horizontally for inspection. On the other hand, the fixed orifice insulators are vertical, and isolation is effected by a downward movement within the tank of a framework carrying the entire circuit-breaker terminals and contacts. It has, therefore, the advantage over the usual vertical drop-down switchgear that there is no lifting and lowering of a heavy weight for isolating; but the design is such that the top has to be hinged or otherwise lifted for inspection of oil and contacts. Fig. 44 also shows a variety of this means of isolating, in

* The author. † Whitehead (Switchgear and Cowans, Ltd.).

which the isolating contacts automatically open with the opening of the main contacts.

Fig. 10 shows a drop-down development (Type 2*d*) that has been used in British and American practice for large installations. In Great Britain also the same type has been installed for 66 000-volt service (Fig. 17). It will be

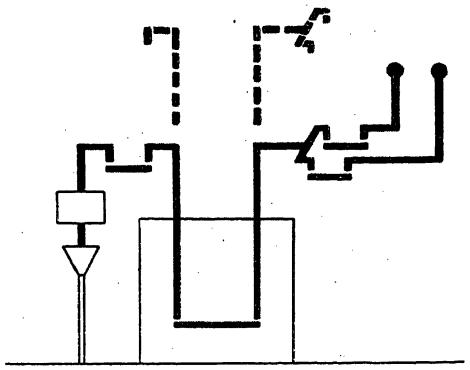


FIG. 15.—Type 3*c*.

referred to again in Section (2)(x), which deals with disposition of busbars and phase separation.

Fig. 18 shows an alternative method in which the circuit is changed over to a transfer busbar in order to avoid the use of a duplicate circuit-breaker for each unit. The connection to the transfer busbar is effected by means of a switch in an oil tank, which also encloses the earthing contacts. This method has been used* in

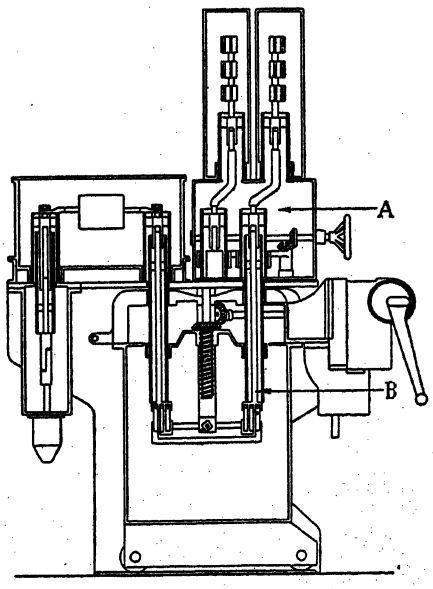


FIG. 16.

A.—Change-over plug receptacles.
B.—Central fitting, movable downwards with circuit breaker open.

switchgear designed and laid down in the factory in 1927–28 for 37 000 volts, and with a breaking capacity of 1 000 000 kVA. The actual processes of isolating and transporting the circuit breakers are facilitated by the use of motor-operated portable trucks.

Fig. 19 illustrates the principle as applied to the

* Allis-Chalmers/Reyrolle.

smaller horizontal-draw-out classes of switchgear. An alternative (Fig. 20), which has been applied for Scandinavian practice, occupies less floor space and indicates another way of earthing the feeder.

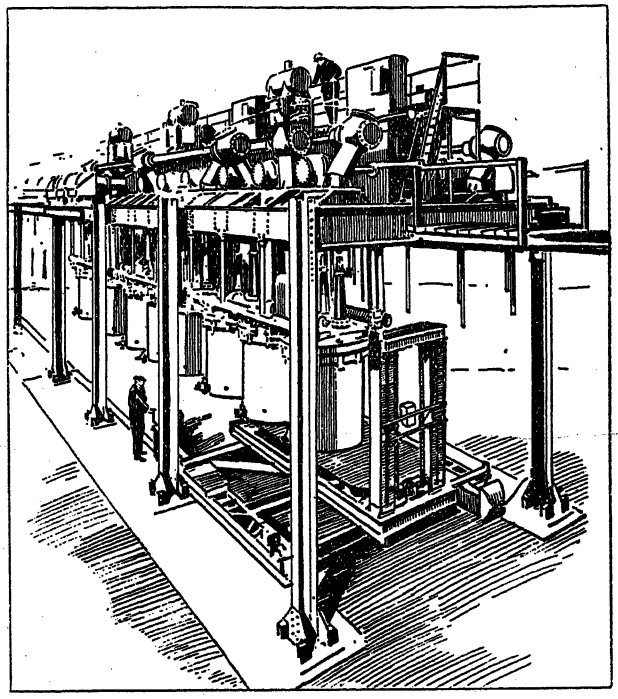


FIG. 17.

Figs. 14 and 21 [Type 3(*a* and *c*)] show a further development* of Fig. 12 for 66 000-volt designs, opening the way to the metal-clad enclosure of even heavier switchgear.

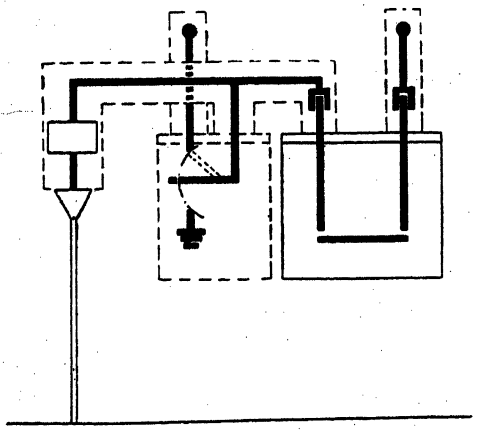


FIG. 18.—Type 2*c* Special (transfer busbar).

(*iv*) *Oil-tight Joints.*

Figs. 19 and 20 show an example of a change in a detail of construction. The creepage of oil through the smallest conceivable opening made it formerly a maxim of good practice to avoid joints under oil. For instance,

* The author, Allan, and Christie.

in the ordinary tank-type circuit breaker the conductors passed into the oil from the top. Modern requirements produce situations in an assembly where conductors and

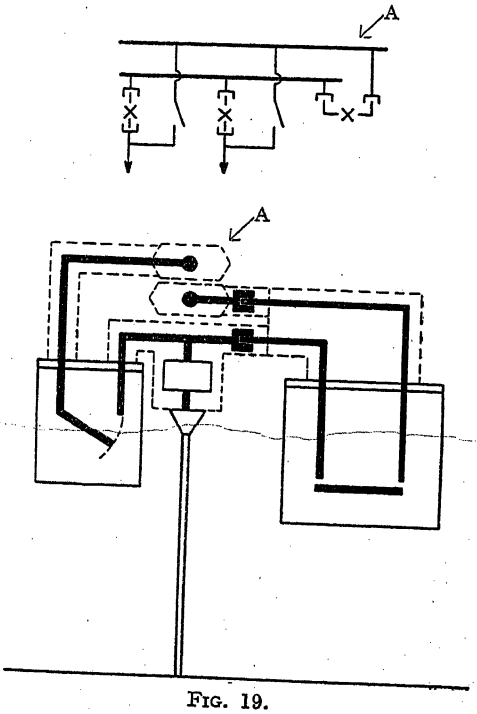


FIG. 19.
A.—Transfer busbar.

insulators must pass through the sides or bottoms of oil-filled enclosures. Cements fail owing to constant changes in the relative dimensions of conducting and

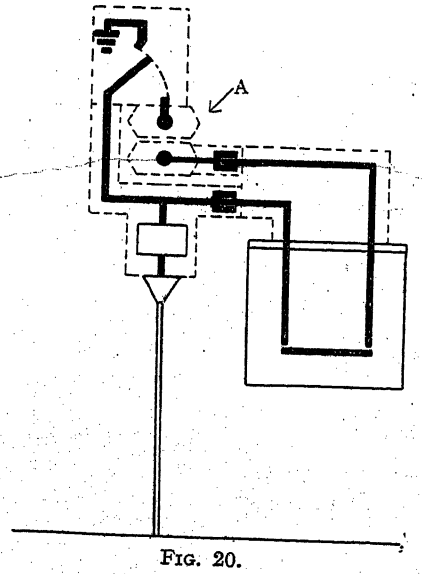


FIG. 20.
A.—Transfer busbar.

insulating materials caused by the differences between the expansion and contraction of the several materials with temperature variations. Moreover, most cements are apt to deteriorate either from contact with oil or from being subjected to high temperature. For these reasons the mechanical joint has of recent years found a more prominent place as an essential detail for securing high quality. Fig. 19 shows the oil-immersed transfer-switch with conductors passing through the top, whereas Fig. 20 illustrates the corresponding conductors passing through the bottom. The mechanical method of securing the oil, and the joint between a porcelain

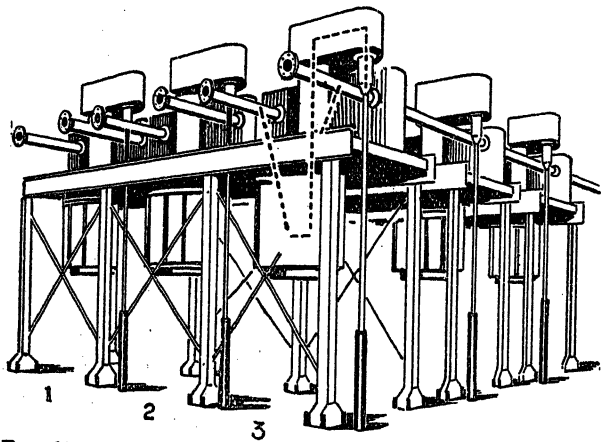


FIG. 21.—Type 3 (*a* and *c*), with switches for isolating, earthing, and change-over, and with vertical removal of circuit breaker.

insulator on the one hand, and the conductor and the metal enclosure on the other, are shown in Fig. 22. When bakelite insulators are used, it is equally necessary to take precautions by appropriate means against leakage.

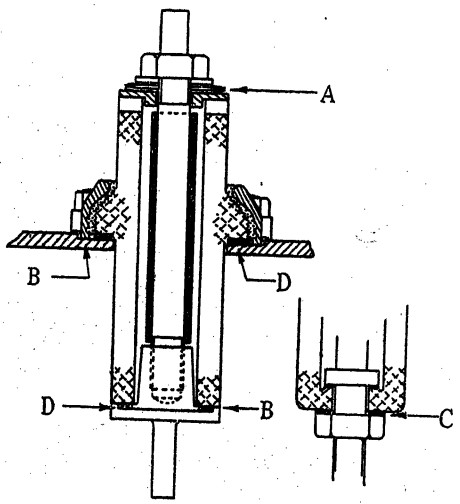


FIG. 22.
A.—Spring washer compensating for expansion
B.—Machined surfaces.
C.—Alternative joint.
D.—Packing.

(*v*) *Transformer Accessibility.*

Compound-filled transformer chambers are the most economical and durable, but when they are used the transformers are not readily accessible or easily removable to the test house for meter-testing. Chambers filled with oil or liquid compound are the alternative, and have

come into wider use. They have large doors, and thus allow access to the terminals and the entire removal of the transformers.

Fig. 23 shows diagrammatically a method devised in Germany. The current-transformer chamber is plugged-in between the circuit breaker and the fixed portion, and the same carriage carries the voltage transformer.

(*vi*) *Horizontal or Vertical.*

There has been some controversy on the relative merits of the original horizontal draw-out and the later vertical drop-down, the outcome being that both types have progressed in size and demand; and each has had its representatives among the new makes evolved during the period under review.

The main claims for the horizontal type are that the removable portion, rolling on a level plane, requires a comparatively small manual effort to isolate it. On mechanical principles, the construction is simple and the disposition of the parts makes the interlocking of the circuit-breaker position with the racking-out components

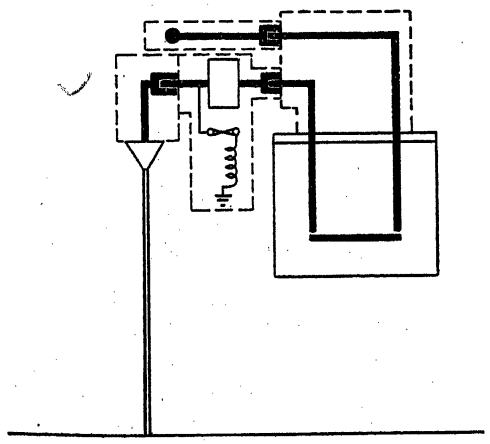


FIG. 23.

very easy. The problems of alignment and co-operation between the moving and the fixed portions are greatly simplified by the use of a true horizontal plane of relation. In contrast with this, the vertical movement involves lowering and raising the heavy removable portion, an operation that for small sizes means much manual effort, and for medium and large sizes necessitates a motor and much incidental gearing, as well as additional means of vertical and horizontal location by guides with such mechanical clearances in all directions as will avoid jamming and ensure true engagement between the fixed and moving contacts and their surrounding parts. On the other hand, the vertical type does economize in floor width, chiefly because less gangway is required for manipulation.

For outdoor use, the roof formed by the busbar chamber when placed above the circuit breakers serves to protect the orifices from the weather, and the vertical orifice not only makes for better clearance of dirt and drainage of moisture from the surface of the insulators, but also lends itself to oil-filling, which is advantageous for very high voltages.

For indoor use, however, the additional height of the one type must be set against the additional floor width of the other when calculating building costs; and, taking everything into account, on the basis of the usual British practice of using single circuit-breakers in preference to duplicate circuit-breakers, and particularly on the score of easy design and accessibility and general convenience in operation, the author's conclusion is in favour of the horizontal type, up to the point at which oil-filling of orifices becomes necessary on account of voltage. Figs. 24A and 24B show a comparison of examples of the two types used in practice on the basis of plans prepared in the same drawing-office.

(*vii*) *Arcing-Contact Classification.*

Known forms of arcing contacts may be classified, as distinct from circuit-breaker classification, as follows: (*a*) Plain; (*b*) Boxed; (*c*) Blast.

(*a*) *Plain Contacts.*—With contacts of this class, the arc is controlled by the general body of oil in the tank, and is subject to deflexion only by magnetic induction from neighbouring current-paths. This class includes all types of arcing contacts that have been in practical service from the beginning, such as sliding, butt, and roller contacts.

With the object of keeping the amount of vaporized metal comparatively small, metals vaporizing at high temperatures have been tried as arcing contacts. Provided suitable means are available for the avoidance of welding, it has been found that the use of steel in this way has the obvious advantage of tending to increase the contact grip by magnetic attraction, thus reducing chattering and arcing when closing on short-circuits. A solenoid-grip contact has been used abroad for the same purpose. In another design, where greater speed of separation was the object, acceleration of the break has been obtained by " flicker " contacts in oil, thus reverting to the principle of the early Ferranti design of high-voltage air-break and oil-break switches. The idea of using separate arcing contacts for making circuit, at closer centres than those for breaking, has been tried for the purpose of reducing the electromagnetic forces when closing the circuit. These " making " contacts have been so arranged, by dash-pot and spring action, that they separate first when opening the circuit. In order to reduce the pneumatic forces tending to push off the circuit breaker, arising from sudden evolution of high-pressure gas between the contact surfaces, several methods have been tried, including the use of small-diameter, spring-loaded, butt-type arcing contacts of tubular form.

(*b*) *Boxed Contacts.*—In a boxed contact, the arc is cloaked by an insulated enclosure, which restricts for a while the expansion of the gas formed by the arc, the outlets controlling the direction of the arc and the gas forces. For example, in the explosion-pot device the gas pressure is confined at the beginning of the stroke. Difficulties have been experienced in making the pots capable of withstanding the high electric and mechanical stresses to which the interiors are subjected when circuit breakers are closed or opened under heavy-current conditions. The old practice of using an insulating lining in a steel container has been largely abandoned in favour

of a chamber constructed entirely of very strong bakelite insulating material.

In America, the "de-ion" device of the air-break type has been developed, in which the arc is split up into a large number of short lengths, reacting to a series of magnetic fields; but relevant discussions there* acknowledge that progress must spring from the crevice and is thus swept through gas escaping from the crevice in the opposite direction.

Contemporary research in Great Britain has set before itself the similar basic aim of achieving peaceful arc-rupturing in oil.

(c) *Blast Contacts.*—All contacts have some form of blast set up around them when operating on short-circuit,

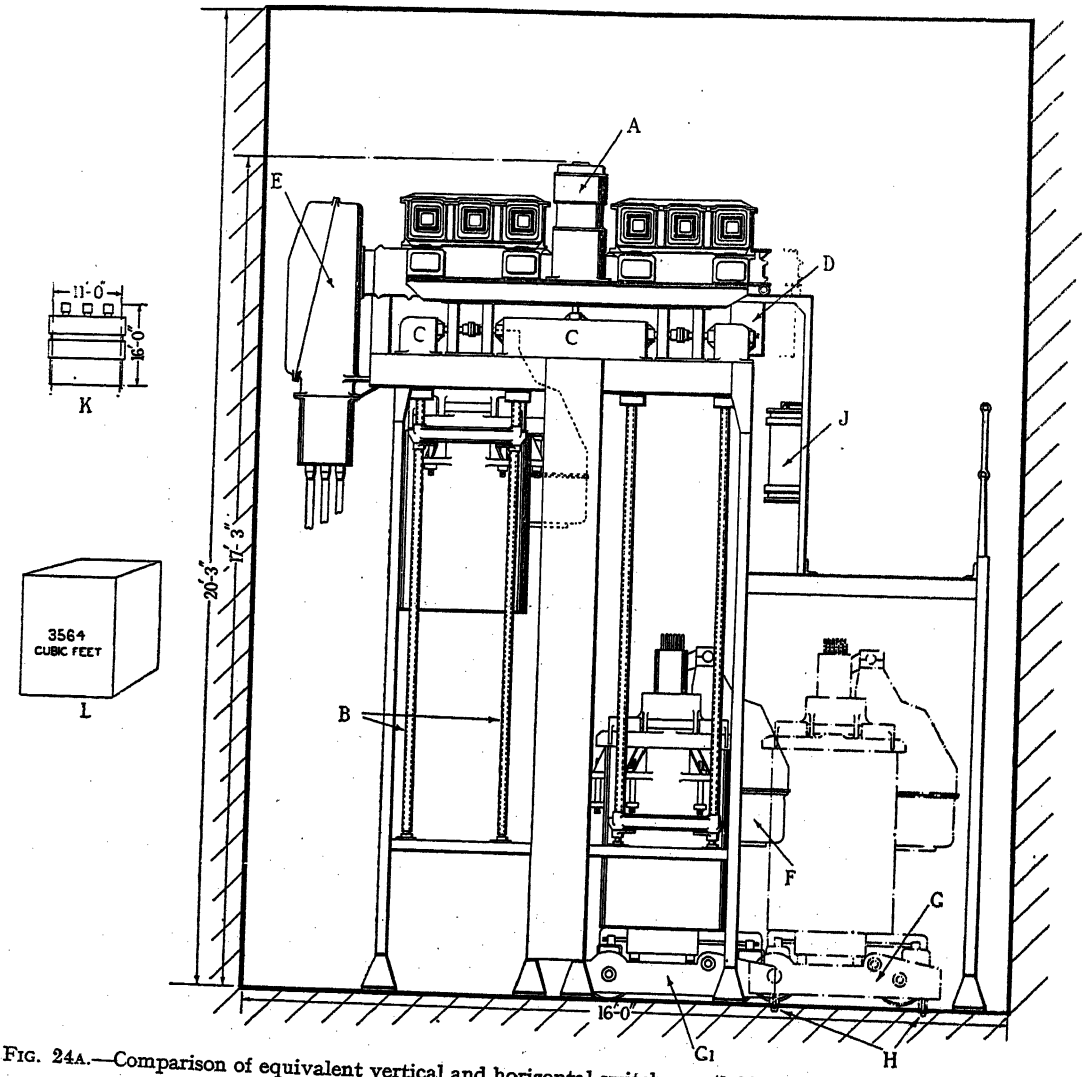


FIG. 24A.—Comparison of equivalent vertical and horizontal switchgear (1 000 000 kVA) (see also Fig. 24B).

Vertical Withdrawal.

A.—Motor operating circuit-breaker lowering-screws B through gear-boxes C.
D.—Voltage transformer.
E.—Current-transformer chamber.
F.—Circuit-breaker closing solenoid.
G.—Truck on longitudinal rails H.
G1.—Truck on transfer cross-rails.
J.—Controller for motor A.
K.—Floor area.
L.—Cubic space.

fundamental present-day practice of using metal-enclosure and oil-immersion. As a result, the oil-break "de-ion" contact has been evolved, in which the arc is drawn between single electrodes within a vertical crevice cut in an insulated box made of horizontal laminations in which horseshoe iron plates are embedded. The arc is moved by a magnetic field towards the closed side of the

* B. P. BAKER and H. M. WILCOX: "The Use of Oil in Arc Rupture," *Transactions of the American I.E.E.*, 1930, vol. 49, p. 431.

because of the gas formed by the arc; but in those called "blast contacts" for the purpose of the present discussion the blast is accentuated by subjecting the arc-path to some additional pressure artificially produced, as, for example, by a flow of oil or other insulating medium.

In one form, which has been applied to a contactor, the path of the arc is crossed by a blast of air created by a piston incorporated in the mechanism. In the air-blast or gas-blast circuit breaker the path is cut and the arc

is guided into a tube by an artificial blast of air or inert gas. The principle has been very fully explored experimentally by the British Electrical Research Association, and in the meantime a type of somewhat similar construction has been put into practice in Germany. The so-called "expansion" switch, which has followed it there, may be considered as belonging to this class. In the other. It is exemplified in the American oil-blast circuit breaker, in which there are two butt-contacts in series, one of which forms an arc before the other. The first arc creates a pressure, which forces oil and gas across the path of the second arc.* This seems to be a natural outcome of experience of the sudden expansion of materials in contact with the arc; but although it was

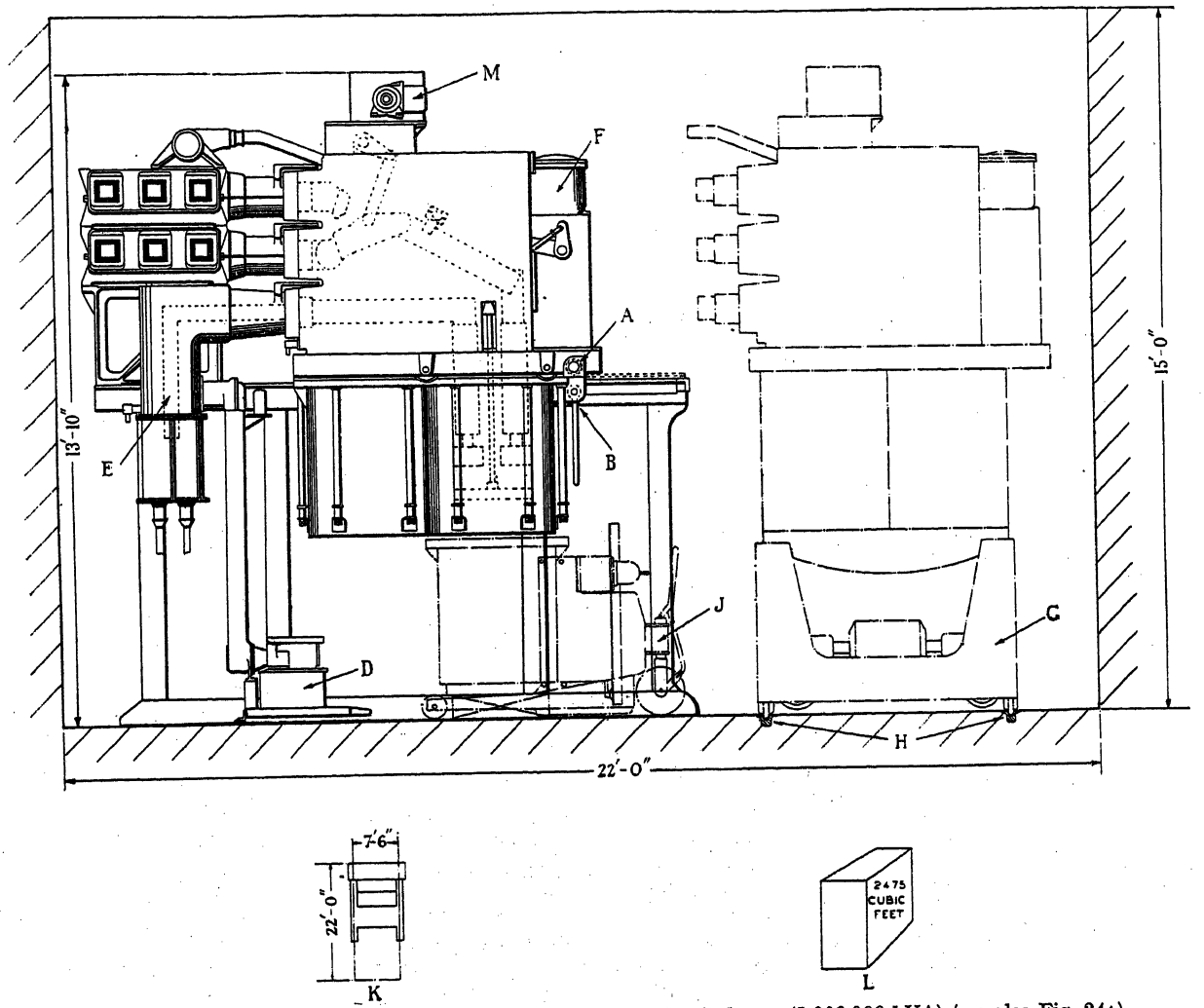


FIG. 24B.—Comparison of equivalent vertical and horizontal switchgear (1 000 000 kVA) (see also Fig. 24A).

Horizontal Withdrawal.
(End-elevation with one frame-standard removed.)

A.—Racking-in-and-out gear operated from handle B.
D.—Voltage transformer.
E.—Current-transformer chamber.
F.—Circuit-breaker closing-solenoid.
G.—Truck on longitudinal rails H.
J.—Bogie for tank transport.
K.—Floor area.
L.—Cubic space.
M.—Motor operating busbar selector switches.

it the arc creates steam or other vapour, which is allowed to expand in a secondary chamber through which the arc has to pass. This type may be regarded as a lineal descendant of the water-break devices of 35 years ago;* and it is also reminiscent of the liquid resistances once thought necessary for charging cables.

In another type of this class, two arcs are formed in a box or chamber, one generating a blast which acts upon

* L. ANDREWS: *Journal I.E.E.*, 1898, vol. 27, p. 487.

known several years ago† it has only recently become available in practice.

Whatever may be the merits of the three classes, the ideal, unobtainable so far, would appear to be an arcing contact in such a simple form that it would eliminate all parts apt to be distorted under mechanical stress,

* R. M. SPURCK and H. F. STRANG: "Circuit-Breaker Field Tests on Standard and Oil-Blast Explosion-Chamber Oil Circuit-Breakers," Paper read at the American I.E.E. Winter Convention, January 1931.

† HILLIARD: U.S. Patent No. 1548799—1925, filed 10th August 1921.

and would have a contact-grip capable of mastering the situation completely; that is to say, it should be so strong as to prevent any serious burning or arcing as the current rises and falls in the cycle, but also, when the current is at or about zero, it should instantly release, and the re-establishment of the arc should be prevented either by the high speed of withdrawal of the contact or by some other adequate means. The form that lends itself best to complete enclosure of the whole circuit breaker, and is not dependent upon some external agency that might itself fail at the critical moment, is the one most likely to survive the long ordeal of tests and practical service that will be necessary before universal standardization can be achieved.

(viii) Electrostatic Stress Distribution.

Corona discharge in orifice insulators, and at the base of pin-and-plug insulators, may not be detected during preliminary testing or from observations under normal working conditions; but occurrences after continuous use on systems operating at 33 000 volts and over have proved the advantage of uniform electrostatic stress along the whole surface of each insulator. Porcelain is

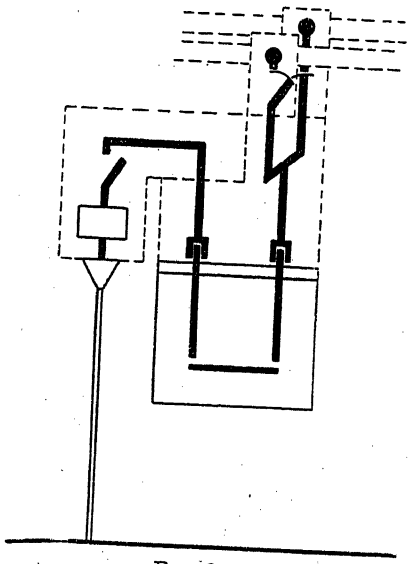


FIG. 25.

effective as a surface insulator, and as such is the best protection from weather and dirt; but it cannot be conveniently shaped to give the full economy in space characteristic of metal-clad switchgear except at the expense of stressing some parts of its surface considerably more than the average. The ideal insulator, therefore, as now required for very high voltages, is one having a surface with the properties of porcelain, and a graded condenser interior.

(ix) Oil-Filled Isolating-Orifices.

From the standpoint of insulation, the isolating-contact orifice is usually the weakest part of the average design, since it is a place where, on account of the contact between the fixed and the removable portion, the fittings are generally in air; and sometimes the clearances have been none too good, particularly when the reduction during the withdrawal or plugging-in of the removable portion is taken into account. Moreover, the orifice introduces an exception to the principle of complete immersion; and, in spite of locking-off doors, men have

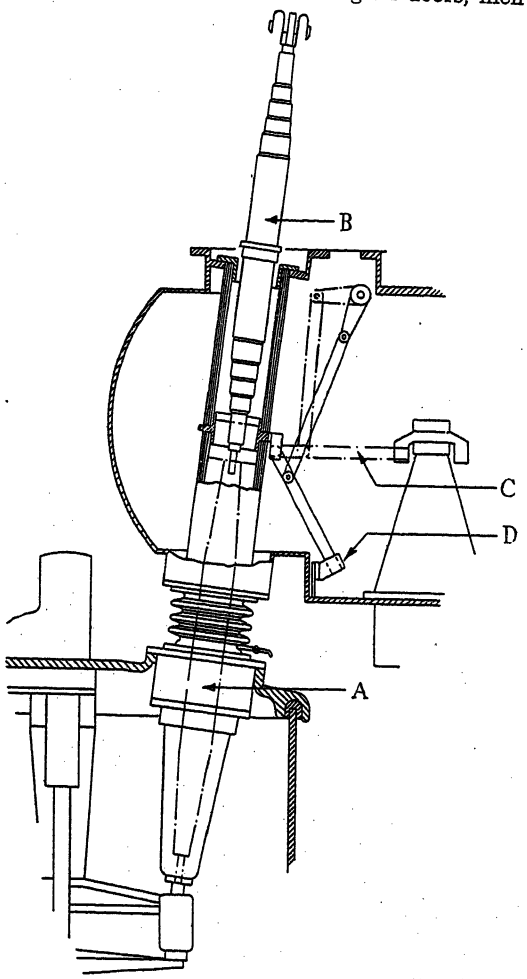


FIG. 26.

A.—Central fitting in circuit and interlocked with earthing switch in open position C.
B.—Central fitting in withdrawn position and interlocked with earthing switch in earthed position D.

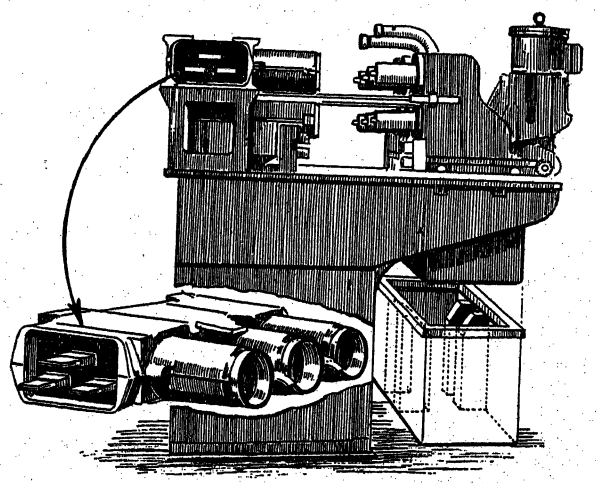


FIG. 27.

been known to put their hands in and make contact with live parts.

Attempts were made as long ago as 1911 to obtain an oil-immersed isolating chamber, and in a measure it was secured in the way illustrated in the author's 1925 paper* (see also Fig. 15, Type 3*c*, of the present paper). In the detail of this design the orifice is contained in the top-plate of an oil-immersed isolating-switch.

Another application† of this principle combined

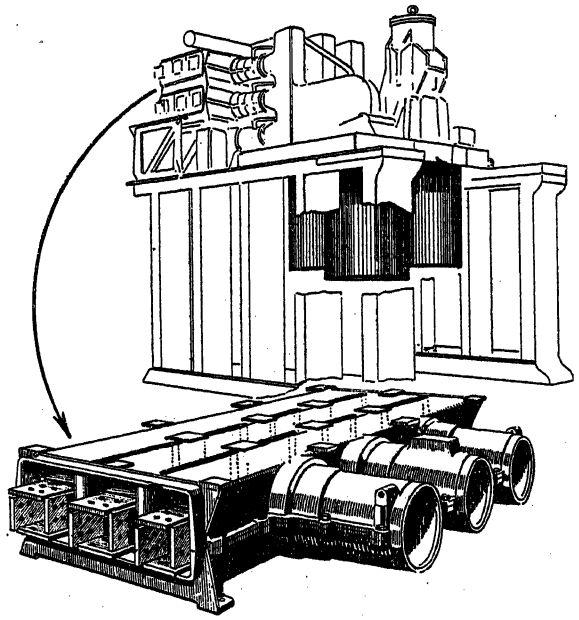


FIG. 28.

Classes (2) and (3), as shown in Fig. 25. The orifice is oil-filled, and has to be emptied before the circuit breaker is withdrawn; but withdrawal is not essential to isolation, and cannot be effected until the conductors in the orifice chamber are isolated on the busbar and feeder sides, and in addition are earthed. By this means the orifice can never be alive when exposed to the air.

A further step in design, Type 3(*a* and *c*), is shown diagrammatically in Fig. 14 already referred to, and in more detail in Fig. 26. After the separation of the central plug contacts, the circuit breaker may be detached from the fixed portion, or, alternatively, it may be examined with safety in its normal position after the oil has been drained from the tank and the manhole covers have been removed. The new development includes the earlier principle of oil-immersed isolation and orifice insulation, and so provides complete oil-immersion of all insulators and fixed conductors, and ensures their inaccessibility when not earthed. Further, since it is compatible with the design requirements of very large apparatus, it makes the construction of self-contained switchgear units for the highest voltages practical for the first time.

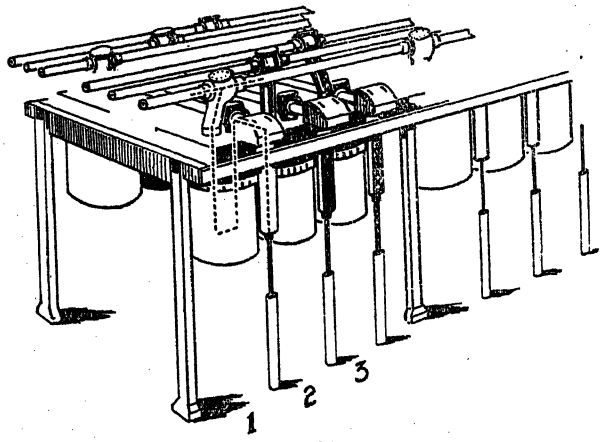


FIG. 29.

(*x*) *Disposition of Busbars and Phase Separation.*

The enclosure of busbars in metal-clad switchgear is a feature bound up with general design, and is an important controlling factor in construction. The earlier methods of enclosing each set of 3-phase busbars, extensively used in actual service, are:—

(*a*) *Three-phase enclosure.*—A single metal chamber, with only insulation between phases: compound-filled (Fig. 27).

(*b*) *Metallic phase-separation.*—A single metal chamber, with metal divisions between phases: compound-filled (Fig. 28).

* *Journal I.E.E.*, 1925, vol. 63, p. 429, Fig. 7.
† British Patent No. 238952: Application date 28th May, 1924.

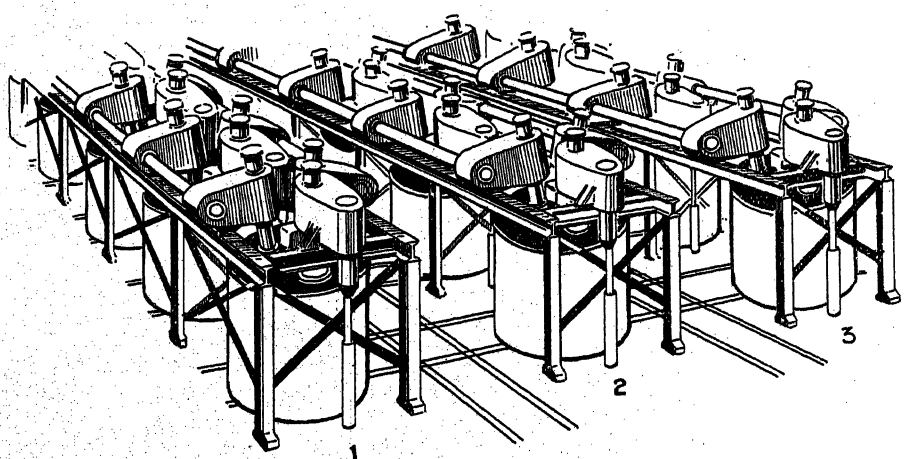


FIG. 30.

The later methods are:—

(*c*) *Single-phase enclosure.*—A group of three adjacent tubular chambers, one chamber for each phase, with the circuit breakers arranged in 3-phase groups, all in one line in the same direction as the busbars: compound-filled or oil-filled (Fig. 29).

(*d*) *Complete spatial phase-separation.*—A tubular chamber for each phase, with the circuit breakers arranged in three single-phase rows, each row in a separate line in the same direction as the corresponding busbar: generally oil-filled (Fig. 30).

In general practice, 3-phase compound enclosure (Method *a*) is used for sizes up to 750 000 kVA and 33 000 volts, and the circuit-breaker phases are wholly or partially separated by partitions in a common tank.

For larger breaking capacities, 3-phase busbars with metal divisions between phases [Method (*b*)] have been adopted in the largest power stations for breaking capacities up to 1 500 000 kVA and 33 000 volts. The associated circuit breakers have a separate tank for each phase, and there is thus complete phase-separation by earthed metal in every part of the switchgear units.

Single-phase enclosure on a large scale with tubular oil-filled busbar chambers [Method (*c*)] was first applied on a trial unit in the form referred to above (Fig. 25); but the practical progress of this system is best known on account of the State Line power-station* installation in America. The original equipment of this was planned on the basis of building-up a casing on site from a number of standard parts, into which the conductors were threaded, but owing to the high cost of "field" work the component parts of later equipments have been produced in "factory-group" construction; that is to say, the bulk of the detail assembly is done in the factory,

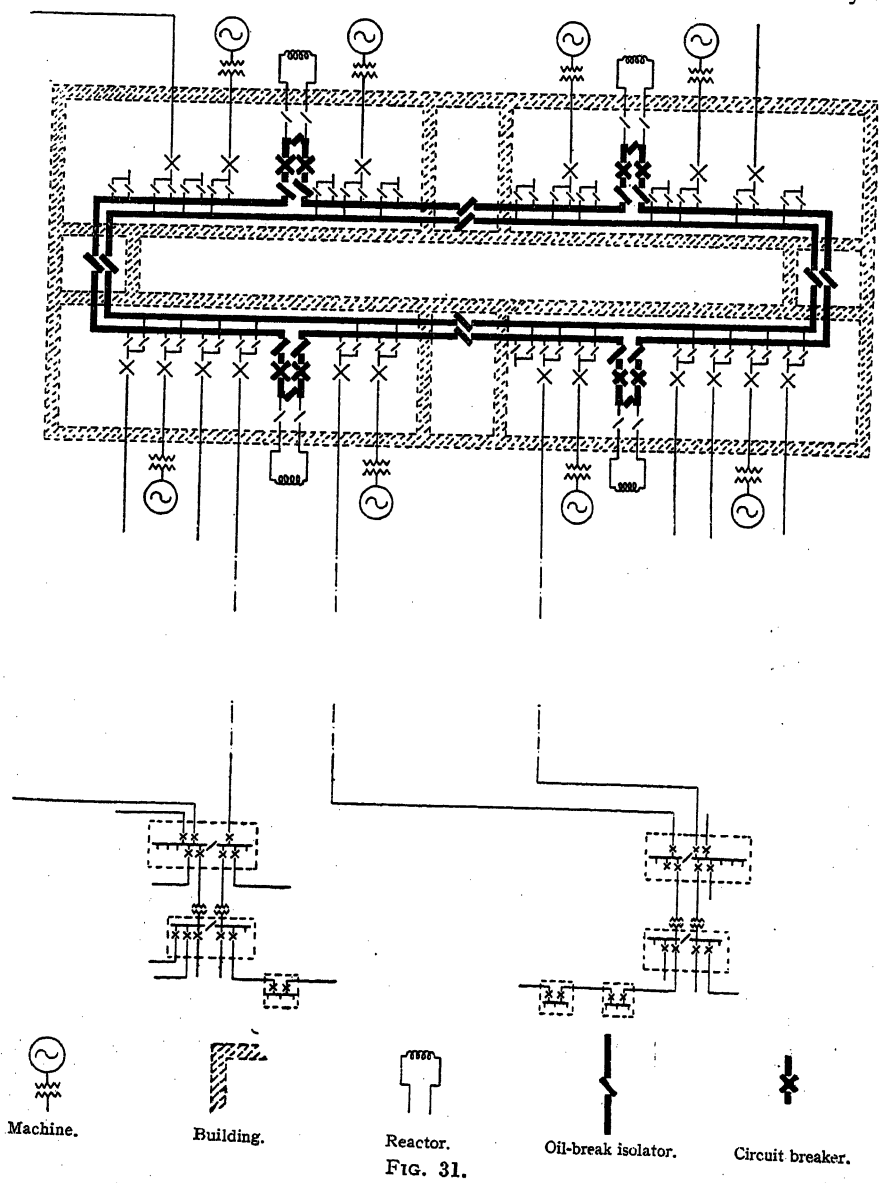


FIG. 31.

* A. M. ROSSMAN: "The Metal-Clad Switchgear at State Line Station," *Transactions of the American I.E.E.*, 1930, vol. 49, p. 397.

the dimensions of individual groups being limited only by transport facilities. In Great Britain, the factory-group system, which was applied to large switchgear in 1918, is now being used for switchgear up to 66 000 volts.

Complete phase-separation for the purpose of ensuring freedom from short-circuits between phases has long had practical application in America for open-type switchgear, as exemplified in those stations in which the phases are actually contained in separate horizontal or vertical sections of buildings; but in metal-clad switchgear of moderate dimensions earthed metal between phases is an equally effective barrier against the spread of faults. Economy in space is secured by it, and since with modern insulation busbar faults are a remote risk, and with metal barriers between phases can only be single-phase faults to earth, which are limited in intensity by neutral-earthing resistors, there seems to be no good reason for greater separation. The case is different in designs for very high voltages, and in exceptionally large constructions,

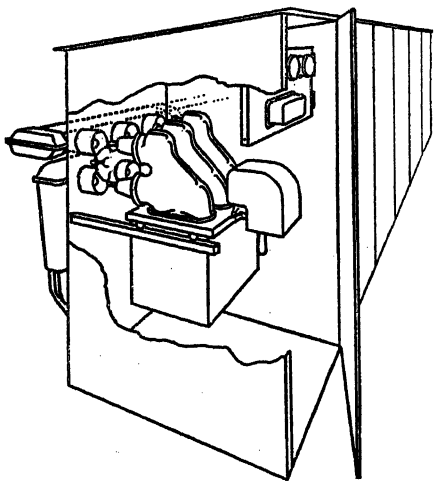


FIG. 32.

because it is desirable to avoid crossing busbars over trunk connections and the like, which is apt to lead to tortuous details. The requisite neatness is secured by spatial separation, in which a straight, clear gangway is provided between phases; and Method (*d*) therefore emerges in the course of the elimination of the complicated.

(*xi*) *Busbars and Building Lay-out.*

Where comparatively weak circuit-breaker enclosures are prevalent, there is much concern about the risk of oil fires and explosions. This has revived the search for oil-less equipment, but in general British practice the saving in space by using oil or compound as an insulating medium, and the general acceptance of metal-clad construction, have secured the retention of oil-immersed circuit breakers characterized by strong enclosures. The occurrence of a few fires, however, has forewarned designers of the possibility that flaming oil or explosive gas may be liberated because of some flaw in construction or operation, such as sustained arcing inside a circuit breaker caused by a failure of insulation. To avoid spreading the damage to adjacent panels, the external enclosure has been made completely fireproof down to that of the smallest secondary connection. It is also preferable that the lay-out of the building should provide for the ready drainage of stray oil. As one form of additional safeguard, the whole equipment has been subdivided into groups of panels, each group contained in a separate switch room, with oil-immersed isolating switches, also in separate rooms, between adjacent groups. Each subsidiary distributing point takes its supply from panels in more than one room, the aim being to lay out the whole of the distribution from the power station in such a way that the complete putting out of action of any room by fire or by hostile attack would not prejudice the supply to any part of the network. The building division in a large power station lay-out is shown diagrammatically in Fig. 31, from which it will be seen that each busbar section extends

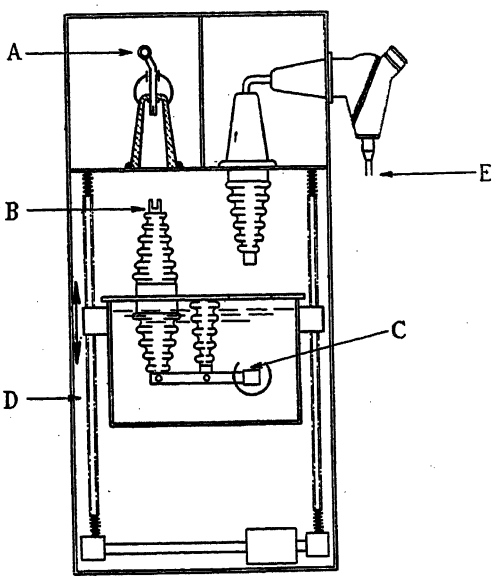


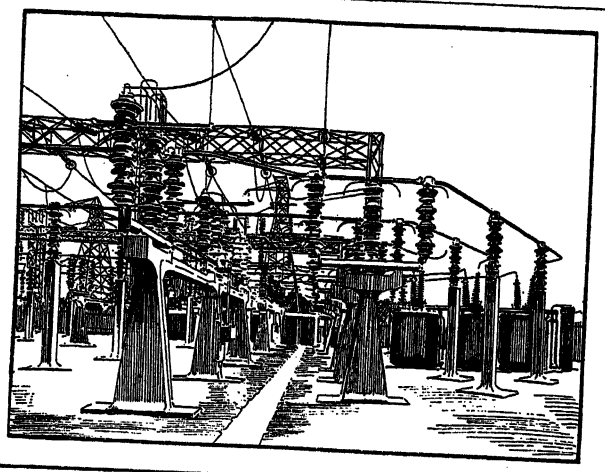
FIG. 33.

A. Busbar.
B.—First make.
C.—First break in oil.
D.—Operating screws.
E.—Cable to circuit breaker.

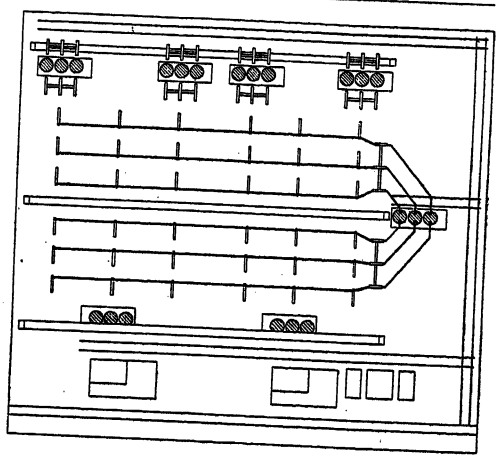
through three distinct rooms. In practice, the building takes the form of an **H**, with the busbar junctions and room-isolating switches situated in the cross-junction.

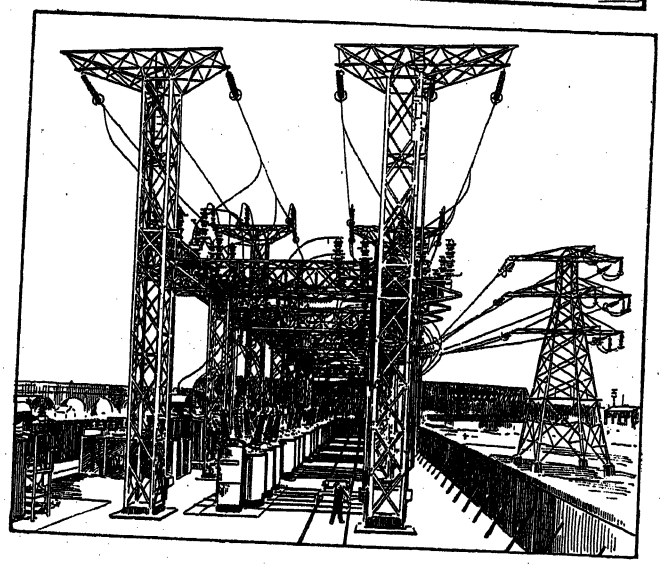
(*xii*) *Outdoor Switchgear.*

Until recently, large outdoor equipments have not been encouraged by British operating engineers, owing probably to fear of having to do maintenance work in inclement weather. Another justification has lain in the fact that indoor metal-clad construction of itself effects ample economy by its large reduction of building costs. In the author's opinion there is much to be said for installing large switchgear out of doors; it has had to be done, because of size, for the 132 000-volt British grid. It is to be expected that the high standard of design now attainable in the metal-clad type with proper care will keep the necessary maintenance work within reasonable limits. The chief gains with this type lie in saving the cost of erecting and maintaining buildings, and in the protection of conductors and insulators from the effects

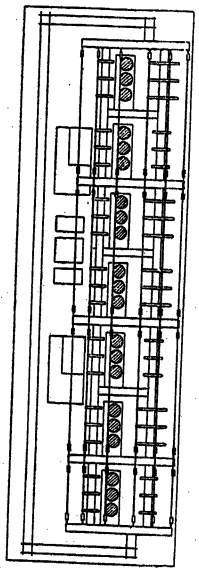


Low.

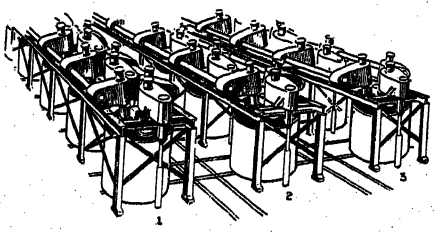




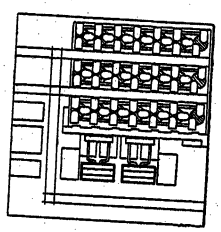
High.

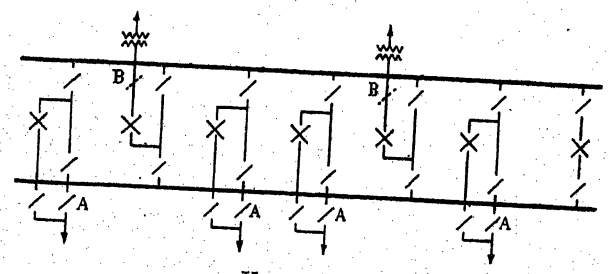


Approximate scale for plans : 1 in. = 100 ft.



Metal-clad.





Key diagram.

FIG. 34.

Switches at A (key diagram) in the existing open-type substation bypass the circuit breaker for one busbar, enabling the feeder to be used with the circuit breaker out of commission. This bypass is not included in the metal-clad lay-out. The metal-clad covering of insulators makes it unnecessary, since it is for maintenance purposes only, to enable insulators to be cleaned and the steelwork painted, etc. On the other hand, the metal-clad lay-out includes isolators and earthing switches at B that are not included in the open lay-out.

of exposure to dirt, water, and lightning. With open-type switchgear, the space factor has become of increasing importance because of the necessity of avoiding accidental contact with live conductors in one section by an operator working on an earthed section or walking near live conductors while carrying metal. The complete covering of all conductors obviates the compulsory provision of large clearance distances. In addition, the splitting-up of the sections of switchgear into fireproof compartments is avoided, and so the whole of the equipment can be seen at a glance. Moreover, remote as the likelihood of

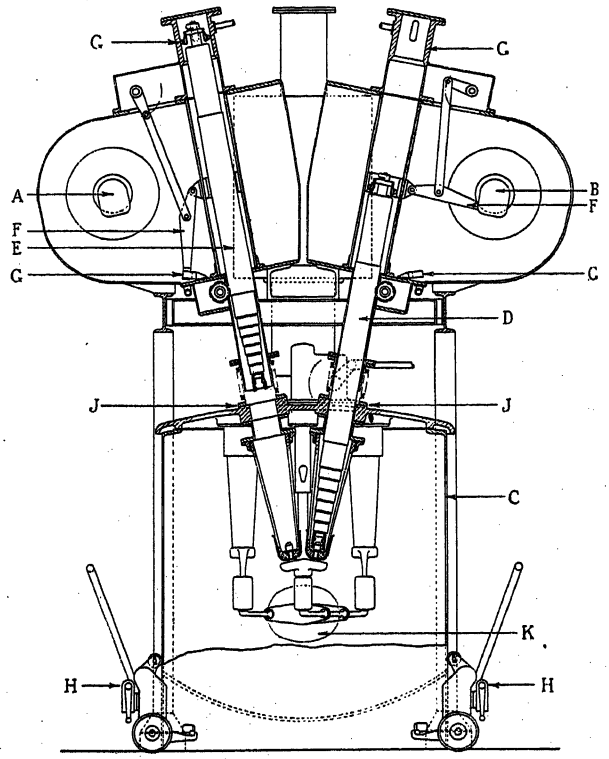


FIG. 35.

A.—Busbar.
B.—Reserve busbar.
C.—Circuit breaker.
D.—Central conductor in service position.
E.—Central conductor in isolated and earthed position.
F.—Isolators and earthing switches.
G.—Earthing contacts.
H.—Portable lifting gear for removal of circuit breaker.
J.—Disjunction flanges.
K.—Manhole.

an explosion may be, if one does occur there is less risk to men who may be working on the switchgear, since they can make their escape more easily. With metal-clad switchgear, whether indoors or out of doors, the primary effects of a fault are local, and the remainder of the switchgear is unaffected. The secondary effects in a building, however, such as smoke and gas, may hinder the speedy restoration of supply; but this would not be so out of doors. Metal and compound or oil are better for the defence and preservation of conductors and insulation than brick walls and roofs. It is common practice to put large transformers outside, and the case for similar treatment of well-protected switchgear is equally strong.

As a half-way measure, switchgear of the smaller sizes is housed in metal kiosks or close-fitting weather-proof protection. A unit, partly housed on these lines and partly outdoor, has been proposed* as indicated in Fig. 32.

(*xiii*) 132 000-*Volt Metal-Clad Switchgear.*

A recent American application of metal-clad principles to 132 000-volt service in the United States includes the use of ordinary circuit breakers having enclosed terminals connected up with metal-covered cables to cable busbars through isolating devices of the type shown in Fig. 33.

It is opportune here to discuss a possible alternative to the existing types of British grid lay-out. Cables are already included in populous districts, where overhead lines are ruled out on account of first cost and danger. The maintenance cost of overhead lines is an item not to be overlooked. It has already been shown (Fig. 30) how metal-clad connections can be marshalled in the substations, and since these are generally situated in industrial or residential districts it is logical to suppose that at some future time the requirements of safety will call for the covering of all conductors in the neighbourhood of the substation. In such districts, also, land is generally increasing in value.

Fig. 34 illustrates, in plan view and in small-scale elevation, a comparison between the open-type "low" and "high" substations and the possible metal-clad arrangement. The last-named occupies about 20 per cent of the ground area of the "low" structure, and about 45 per cent of that of the "high" structure. The reduction of head-room in the substations would avoid any objections on æsthetic grounds to obtrusive overhead structures.

Fig. 35 indicates the prospective further progress of Type 3(*a* and *c*) (Fig. 14) on a large scale. The framework and the tank and circuit-breaker lowering mechanism, usually convenient up to 66 000 volts, are too bulky and heavy for higher voltages. The proposal therefore is to give access through manhole doors for normal inspection after isolating and earthing all conductors, and to provide for complete removal of the circuit-breaker portion with the aid of portable bogies only. The drawing shows a cross-section in the plane at right angles to the line of busbars in order to illustrate the operation of changing over from one busbar to the other. The ground space occupied by the complete unit panel is very little more than is required for the now familiar grid circuit-breakers, and the necessity for large clearances is avoided by the immersion of all conductors and insulators in oil. The general lay-out has already been referred to (Fig. 30).

(*xiv*) *Voltage Measurement.*

Progress has been made in the development of condenser couplers (Figs. 36 and 55) with the object of substituting them for the usual voltage transformers in very-high-voltage circuits. The high-voltage windings of the transformers have always been a possible source of weakness, necessitating high-voltage isolating devices and fuses. Condenser couplers eliminate fuses because they have no high-voltage primary windings; and in

* Allis-Chalmers Manufacturing Co.

electric strength they are equal to or better than any other main insulator.

(xv) Busbars.

The increase in current ratings has entailed research to ascertain the best construction of busbars and to enable the correct current densities to be selected to avoid overstepping accepted temperature-rises. Fig. 37 shows the average current densities that have been found necessary in practice to limit hot-spot temperatures to 50 deg. C. rise. The values are based on the results of tests of different sizes and arrangements of busbars with thermo-couples in contact with the copper in several positions. In the past it was the practice for users to specify busbar sections, or current densities, or both, but in metal-clad switchgear it is the ultimate temperature alone that matters, and the permissible maximum densities may vary considerably with the design and the ambient conditions. The ideals of complete enclosure and of keeping down temperature conflict with one another, but one objective is common to both, namely, to keep the insulation permanently perfect. The maximum internal temperature is the criterion of endurance, and it is therefore this, as has

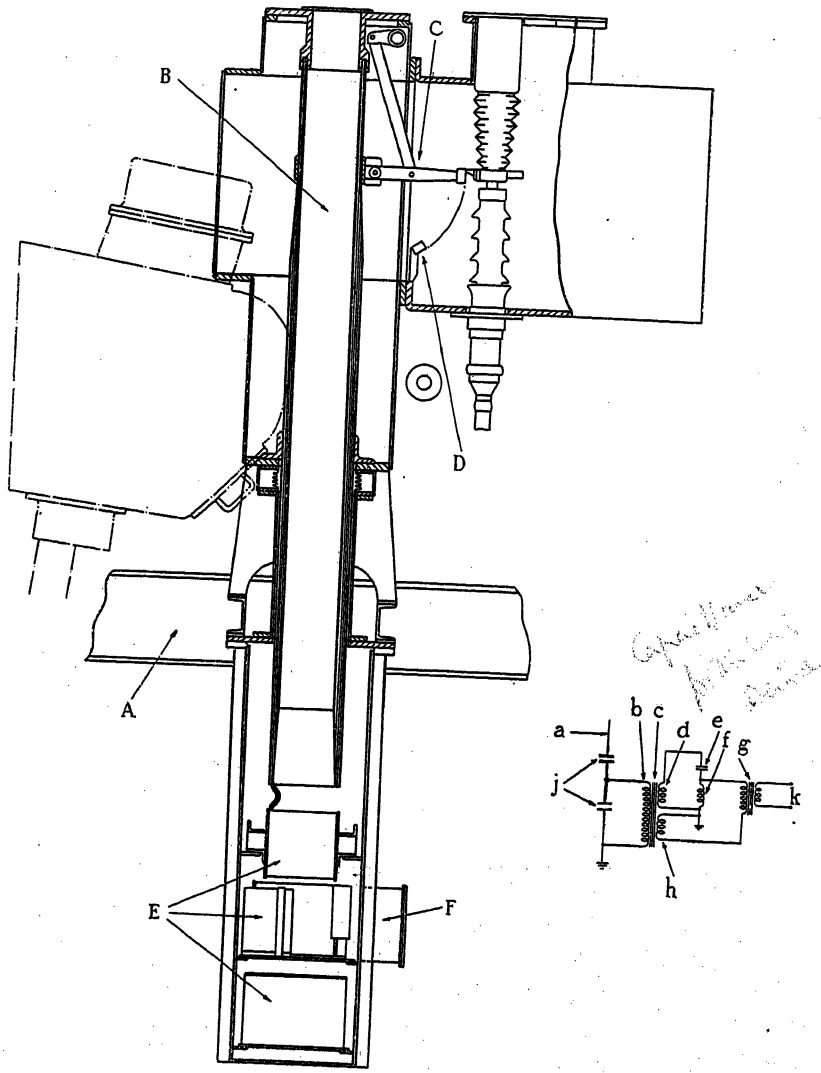


FIG. 36.

A.—Switchgear framework.
B.—Condenser coupler.
C.—Isolating switch.
D.—Earthing contact.
E.—Auxiliary transformer and secondary-voltage regulating equipment.
F.—Secondary terminal-box.

Inset (diagram of connections):—

a.—High-voltage lead.
b.—Tapping from last layer.
c.—Transformer.
d.—Secondary winding.
e.—Tuning condenser.
f.—Variable reactor.
g.—Auxiliary voltage-transformer.
h.—Tertiary winding.
j.—Bushing.
k.—Secondary terminals.

been said, rather than the temperature-rise, that matters most. Hence it is necessary to determine the maximum permissible temperatures for all the materials used. Insulating materials are the most vulnerable, and 80° C. is a reasonable limit for procurable qualities of those in common use in switchgear to-day; the permissible temperature-rise is therefore the difference between 80° C. and the ambient temperature. Although it has been the standard practice to permit a rise of 30 deg. C. for currents up to 2 000 amperes, and of 40 deg. C. for currents above this value, there appears to be no longer any reason for this distinction. It is true that it is more difficult to keep the temperature down in metal-clad switchgear at the heavier currents, but, since it is mainly a question of durability of insulation, the requirements should be the same for low-current ratings as for high-current ratings. The curve shows that ratings of 2 500 amperes and over necessitate abnormal sections of copper, or special arrangements of busbars, in order to keep the temperature within safe limits. This, together with the abnormal stresses set up when short-circuit currents are carried or broken, determines a

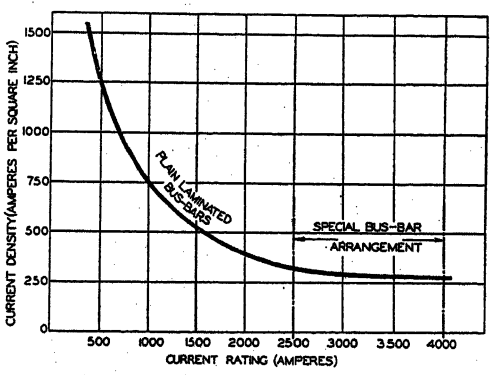


FIG. 37.

practical limit for the current rating of main power-station panels.

This limitation of current raises the question of the suitable working voltage for the switchgear of a generating station of any given size, particularly in view of the present tendency towards a need for greater breaking capacities. Obviously, since for a given breaking capacity the current is inversely proportional to the voltage, a voltage chosen too low for conditions involving some definite breaking capacity must lead to very difficult problems arising out of too high current values. Hence, speaking generally, there is a best (or at least an advisable minimum) voltage for any given breaking capacity. It is difficult to establish a rule for a problem into which so many variables enter; but a very rough approximation might be that for a 3-phase circuit breaker, within the range of present standard ratings, namely up to 1 500 000 kVA, the numerical value of the minimum working voltage of switchgear should be, say, something of the general order of the 1/125th part of the numerical value of its breaking capacity in kVA.

(*xvi*) *Switching Capacity.*

"Switching capacity" is the term used here to describe the operating ability of a circuit breaker as a protective device for making and breaking current. In practice as it stands to-day, there is need to clarify the idea associated with the terms "rating," "performance," and "selection," when used in relation to making and breaking under short-circuit conditions.

Ratings have been established in B.S.S. No. 116–1929, Clause 46 of which specifies that the standard kVA ratings of Table III shall be based on a schedule of currents given in Table IV and on the line voltages given in Table I. In the standard conditions for determining making capacity and breaking capacity, whereas a power factor of 0·1 lagging and the duty-cycle are included, recovery voltage is not prescribed. Recovery voltage is also a condition of severity, and therefore the present specification of standard conditions, under which the rating is assigned, is incomplete.

Previously manufacturers had established certain dimensions of circuit-breaker enclosures based upon the experience of practical service. These were checked from time to time with available data; but in the absence of large test plant the data had to be derived from tests on plant of a size small in comparison with the range of ratings that had to be declared. It is not surprising, therefore, that some of the designs made to the old empirical ratings have required revision in respect of strength of detail components.

Performance is the proved ability of the circuit breaker under test conditions, and, like rating, should be based on the current broken and the severity of the other conditions of the circuit in which the test is made. The conditions include the size and the electrical and mechanical characteristics of the generator, and the internal and external impedance of the circuit, which control both the power factor during the arcing period, and the value and rate of growth of the recovery voltage on the extinction of the arc.

Selection is the choice of circuit-breaker rating for a given service condition, and must be in accordance with the recovery voltage and power factor of the short-circuit in the vicinity of the circuit breaker on the system, and the margin for safety required, having regard to the relative importance of the position. For a given fault current the demand upon the circuit breaker is greatest with low power factor and high recovery voltage. This occurs when the fault current is restricted by reactance, as in a fault on the secondary circuit of a transformer near to a large generating station. The demand is least when the power factor is high and the recovery voltage is low; but this seldom occurs in practice. Between these two extremes comes relative easement by low recovery voltage or by high power factor. An example of low recovery voltage conditions is a fault near isolated generating plant, which stores up little electro-mechanical energy and has a large voltage decrement. High power factor is associated with a remote fault, in which the current is small in comparison with the capacity of the plant, and the circuit, in the absence of transformers, is mainly non-inductive.

An international method of interpreting short-circuit oscillograms has yet to be determined. In the author's opinion, rated breaking capacity should be based upon performance under some clearly-defined standard test-

conditions. A suggestion for discussion, intended to assist in the establishment of a suitable standard circuit, is included in Appendix I. The effect of departure from test conditions must be very clearly understood. For instance, let it be supposed that a circuit breaker has had some definite rating assigned to it under the standard conditions; then, if the same circuit breaker is used in a situation where, other things being equal, the power factor and the recovery voltage depart from the standard, the performance may be expected to differ also, and it may in fact become necessary to select a circuit breaker of a larger or smaller rating, as the case may be.

In spite of doubts that have been expressed about the consistency of oil-break circuit-breaker operation, given a correct understanding of the conditions typical British commercial oil-break circuit breakers will break short-circuits with reasonable consistency well above the rating assigned to them in accordance with B.S.S. No. 116—1929, at a recovery voltage in accordance with the

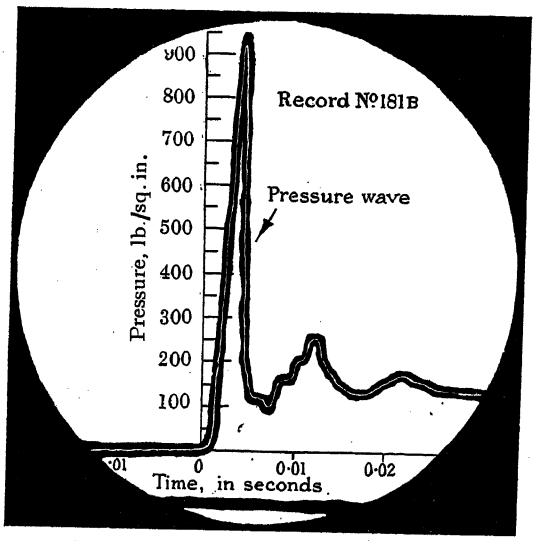


FIG. 38.

service conditions of an interconnected network. (This is shown in Appendix II.) These conclusions are based on experience with circuit breakers having satisfactory mechanical construction and insulation. Obviously, the circumstances may be entirely different if there are such defects as sticking of a circuit breaker, a tendency to reclose when opening, pumping at the contacts when closing, or failure of insulation, any of which may cause sustained arcing, which, even if of short length and of only a few seconds' duration, may entirely alter the stress within the enclosure. An excessive succession of arc impulses may build up stresses that venting devices are incapable of relieving with sufficient rapidity, and such stresses will exceed many times that of the maximum gas explosion. On the other hand, it must be remembered that enclosures which pass heavy and steady hydraulic pressure tests will withstand impulse shocks of much greater intensity. For example, a tank designed for a steady hydraulic pressure of 150 lb. per sq. in. is shown by a pressure record (Fig. 38) to have withstood an impulse pressure of 950 lb. per sq. in., and experience proves that impulse pressures up to 10 times the steady hydraulic pressure can be withstood satisfactorily.

Closing on short-circuit is perhaps so rare that in the past it has not been required of circuit breakers in standard specifications. It has been a debatable point whether the circuit breaker should trip free, or go right home first. A trip-free circuit breaker that does not close completely may destroy itself in pumping caused by the pull of the closing solenoid or of the motor yielding to the repelling forces before the trip has time to operate; and even without pumping there remains the chance that the circuit breaker may attempt to break at the maximum wave of the short-circuit transient without having the full benefit of the quick-break mechanism. A further argument in favour of ability to go right home lies in the fact that the service duty of any circuit breaker is to isolate the section controlled by it; and therefore, if a circuit breaker is closed on a "through" fault, another circuit breaker, namely, the one controlling the faulty section, is the one that should open, and not the one that is being closed.

It is possible that currents on the closing of circuit breakers on a short-circuit may sometimes be so large, and closing right home so difficult to achieve, that a less expensive alternative may be sought; for example, the addition of some discriminating device that will actually prevent the attempt when the circuit condition is such that these heavy currents would be encountered.

(xvii) Stress Limitation.

The first requirement of a circuit breaker is that it must be capable of withstanding any current or voltage condition within its rating, without establishing an arcing fault in itself. Next in importance is that during the arcing period it shall create the minimum effective stress within its enclosure. The strong tank and top-plate, in contrast with the earlier thin tank, are in themselves a means to this end. The strong walls resist the pressure and restrict the arc-containing bubbles. The turbulent gases at high density, which form the bubbles, help to prevent restoration of the arc after the current has passed through zero. Paradoxical as it may seem, a pressure created within the tank is actually a stress-limiting factor in circuit-breaking.

It is also essential, for stress reduction, to make the contacts sufficiently robust to withstand the mechanical forces due both to the magnetic field and to the thermal effects of the current and consequent arcing. The problems of the circuit breaker may not be entirely solved by the use of intricate arcing contacts, even should tests show promise of stress reduction. Devices of elaborate shapes and constructive features are costly and difficult to inspect and to maintain, when compared with plain arcing contacts separating in oil. If contrivances designed to improve breaking capacity include in themselves additional features, they tend on that account to introduce weakness either mechanically or electrically; and in the event of failure the final defence must depend upon strength of enclosure. Moreover, the elimination of oil does not necessarily give immunity from trouble, since the insulation is more apt to fail because of its exposure, and arcing in air creates stresses

and widespread damage, constituting a danger to persons and a likely source of damage to buildings.

(*xviii*) *Saving Switchgear.*

The elimination of superfluous switchgear tends to increase safety, on the principle that there are fewer parts to go wrong; and for an equal cost the simpler switchgear has better components, and therefore the risks are still further reduced. On step-up units the use of switchgear on the low-voltage side of the transformers only has effected a saving in high-voltage circuit breakers; and the principle can be applied wherever the high-voltage side of the transformers and the line are independent units. Similarly a saving in power-station switchgear is effected by using one circuit breaker to control the generator and its step-up transformer. Incidentally, it has been a great advantage to do this in capital power stations when generating at 6 000 or 12 000 volts, because it avoids the wasteful cost of conductors for very heavy currents.

When other connections come from the line, as happens with tees, parallel feeders, and ring mains, the cost of high-voltage switchgear must be faced. The "single-switch" substation idea, due to Mr. J. R. Beard, has been adopted to good effect on the 132 000-volt grid, three switches serving where five would normally be required for two feeders, two transformers, and a busbar coupler (Fig. 39).

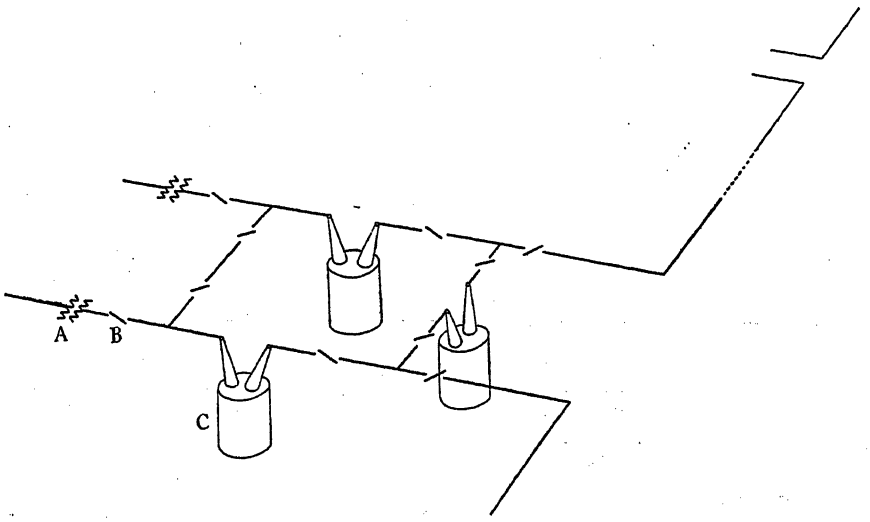


FIG. 39.

A.—Transformers. B.—Isolators. C.—Circuit breakers.

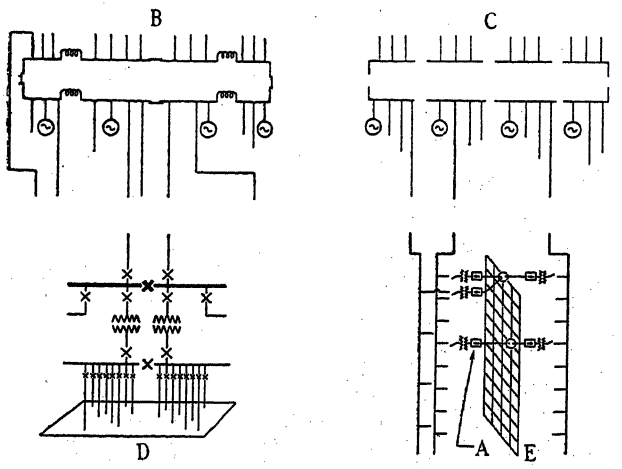


FIG. 40.

A.—Network protectors.
B.—Closed busbar system.
C.—Divided busbar system.
D.—Distribution area as normally used in Great Britain.
E.—Low-voltage network (solid).

The lay-out and connection to the low-voltage distribution may have a material effect on the breaking-capacity demands on the transmission switchgear. For example, the generating plant, when "synchronized at the load"* as an alternative to paralleling at the bus-

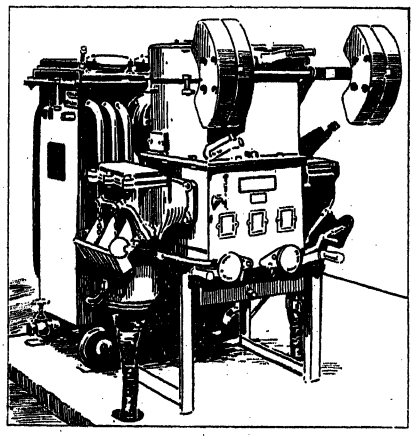


FIG. 41.

Diagram of connections as in Fig. 42, but with overload cut-out in tee-off to consumer's transformer.

* Three papers, "Synchronized at the Load," *Transactions of the American I.E.E.*, 1929, vol. 48, pp. 1079–1107.

bars, utilizes the load transformers and network as impedance. Fig. 40 shows the contrast between the running condition of the closed busbar system and that of the divided busbar. The latter system has introduced into American practice the automatic "network protector," which is a circuit breaker with automatic discrimination in respect to voltage, synchronizing, anti-pumping, and direction of flow of power. The system requires comparatively small circuit breakers near the source of power, since the total capacity is split up into relatively small sections instead of all being tied to one busbar. The reduction in short-circuit fault-current values on the various parts of the system, compared with those obtained in more usual supply and distribution systems, is shown by the following figures, which have been calculated on an assumed symbolic system:

Type of System.

Equipment	"Synchronized at the load" (low-voltage network)	Paralleled at the busbars
	Maximum fault kVA	Maximum fault kVA
Switchgear at source of supply	50 000	150 000
High-voltage circuit breakers near the load	There need be none	131 000
Low-voltage circuit breakers near the load	1 850	31 400
Low-voltage cables designed to burn clear on the occurrence of an "internal" fault	16 000	There are none designed to burn out, since radial feeders are usual, with protection by fuses or circuit breakers

Consumers' outdoor substations can be very simply equipped with oil-immersed isolators in the way indicated in Figs. 41* and 42, when no automatic control of incoming and outgoing feeders is required. An adaptation in a group of three units, illustrated in Fig. 43,

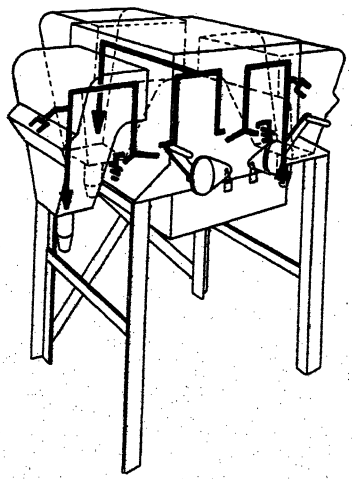


FIG. 42.

allows for the coupling of two pairs of sectionalized feeders, with isolation, earthing, and testing of any of the four cables, and complete isolation of the switching units of either pair of cables; that is to say, it is equivalent to non-automatic 5-panel switchgear.

* Cook and Kingsbury.

Fig. 44 shows a fuse that trips a switch,* and is thus an additional example of combinations of fuses with switches designed to avoid the usual trip coils and current transformers.

Group-switching may be adopted to reduce the dimensions and possible short-circuit conditions of feeder circuit-breakers, where there are a number of feeders branching from one source. The circuits are so arranged that all heavy short-circuits are cleared by the group circuit-breaker before the faulty-feeder circuit-breaker trips. After the latter has opened, the group circuit-breaker recloses, and the healthy feeders continue working.

In one form of the arrangement it is intended that the less severe faults shall be cleared by the feeder circuit-breakers; but the objection to this is that a small fault may grow into a serious short-circuit during the operation of the comparatively small feeder circuit-breaker, which may thus be caused to fail seriously. The alternative is to have all faults cleared by the large group circuit-breaker; and there are two main systems for doing this, one with pilots and the other without them.

The principle of group-switching with pilot wires, shown in Fig. 45, involves simple electrical interlocking between the circuit breakers; and the proposal for

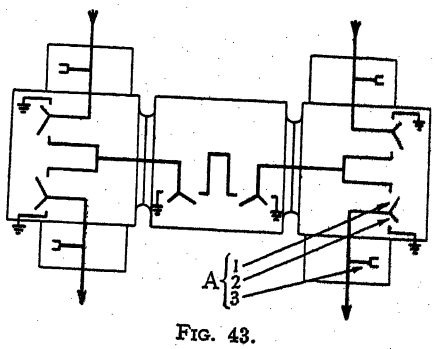


FIG. 43.

A.—Interlock between:—
1. Main switch.
2. Earthing switch.
3. Testing plug.

operation without pilots, which has been called "sequential group-switching," is illustrated in Fig. 46, where it is shown that each feeder circuit-breaker has two trip-coils mechanically interlocked in such a way that one is made ready to trip the circuit breaker on the occurrence

* Page and Astbury.

of a fault; but is not allowed actually to do so until it is released by the other, which is an under-current or under-voltage coil. This release does not take place until the

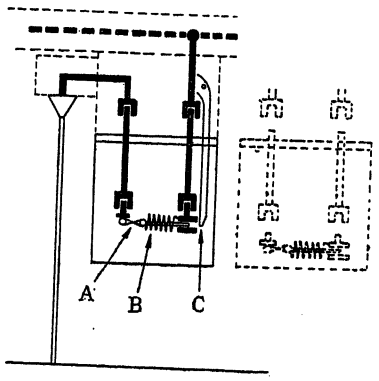


FIG. 44.

A.—Fuse.
B.—Kick-off spring released by fuse blowing. } Mounted on plunger bar of circuit breaker.
C.—Tripping lever.

current in the coil has died away; that is to say, until the group circuit-breaker is open. The group circuit-breaker itself has an over-current or earth-leakage release, and is provided in addition with an automatic reclosing device, which operates in about 0·6 sec., and so restores the load on the remaining healthy feeders. The system, since it requires no pilot, is applicable to a number of remote branch feeders connected by cable to the group circuit breaker.*

* Andrew.

(xix) Safety of Men Working on the Line.

The systems of earthing a cable for the safety of men working on a line,* although they have undergone but little change, have been the subject of much discussion, particularly in respect of their application in mines.

The point has arisen that when the circuit breaker is closed for earthing it must not trip out on any account. Since circuit breakers are generally of the free-handle type, this means the addition of some mechanism to lock-off the tripping-device. Interlocks must be very thorough, to avoid the risk that the lock may be left on at other times when the switch is required to be trip-free.

In regard to the plug type of earthing, complaints have been made that the fitting of the plugs in preparation for earthing is too laborious. One alternative method is shown in Fig. 47. The earthing switch is incorporated in the circuit-breaker tank, and interlocked with the circuit-breaker handle and racking-gear. The main circuit must be open before it is possible to make the earthing contacts, and when they are made the handle is padlocked and the circuit breaker is so locked that it cannot be withdrawn. Therefore the earth cannot be removed by any mischance, the only way being to remove the padlock and to open the earthing contact by hand. It can then be padlocked again in the open position, and the circuit breaker can be used in the ordinary way.

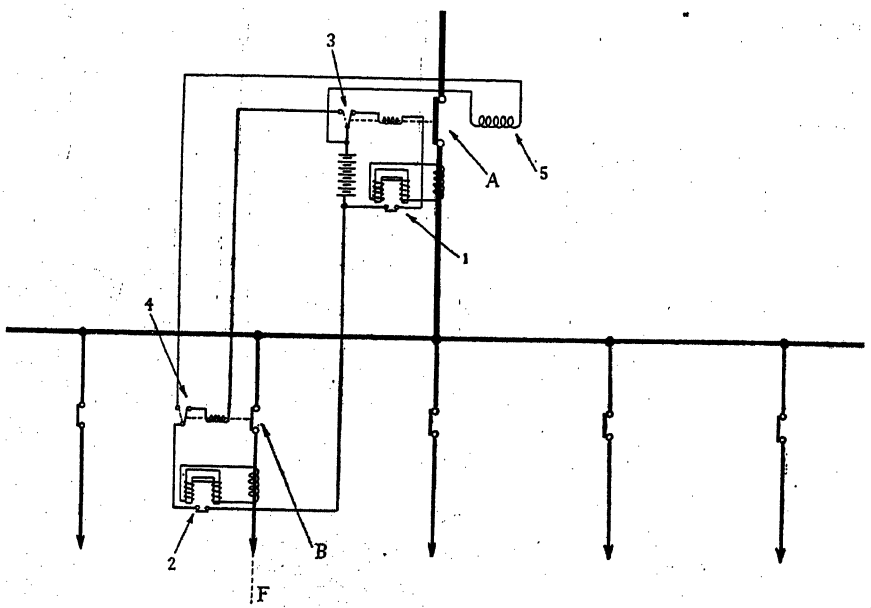


FIG. 45.—Principle of group-switching with pilot connections (necessary time-delay devices and reclosing contactor omitted for simplicity.)

On a fault at F:—
Relay 1 operates, closing trip circuit of group circuit-breaker A.
Relay 2 operates, but does not trip feeder circuit-breaker B until group circuit-breaker A trips, throwing over switch 3 to dotted position.
B trips without load, and throws over switch 4 to dotted position, thus reclosing group circuit-breaker by coil 5.

The same point arises in power-station and substation practice. When a cable is definitely earthed for men working on a line there should be no risk that the circuit breaker will trip out accidentally or by the act of an unauthorized person; and to ensure this the tripping

* *Journal I.E.E.*, 1925, vol. 63, pp. 437 and 438, Figs. 24 and 25.

mechanism must be locked off. This introduces the secondary hazard that the circuit breaker may be racked in erroneously while it is locked in the closed position. Normally a circuit breaker has an interlock between the racking-in and the off position, which automatically trips a closed circuit-breaker during racking-in; but if a part of its mechanism is jammed by an improvised pin or other device foreign to its normal construction, the automatic trip is ineffective. This is not an imaginary danger; it has actually happened that, owing to the insertion of such a pin, a closed circuit-breaker was seriously damaged by arcing at the orifice contacts on being racked in.

Care must therefore be exercised in the selection and use of properly-designed devices for locking-off the tripping mechanism. They must pin down some primary lever, and at the same time positively prevent movement of the racking handle. Such a device, illustrated in Fig. 48, is in the form of a locking bar securely fastened and padlocked into position. The bar has two pins, and the holes are so arranged that only the correct bar, which is made to exact dimensions, will effect the desired purpose. Moreover, the bar is chained to the rest of the earthing equipment.

The system of plug earthing is not always applicable, and, as an alternative, a separate oil-immersed earthing switch has been embodied in the initial design of each unit panel, interlocked with isolating switches, and preferably, in large switchgear, closing on one phase at a time. This phase-by-phase earthing is a precaution reducing the extent of the damage caused in the event of the accidental earthing of a feeder alive from the far end, the resultant damage being then limited to that of a single-phase fault to earth through the earthing resistance.

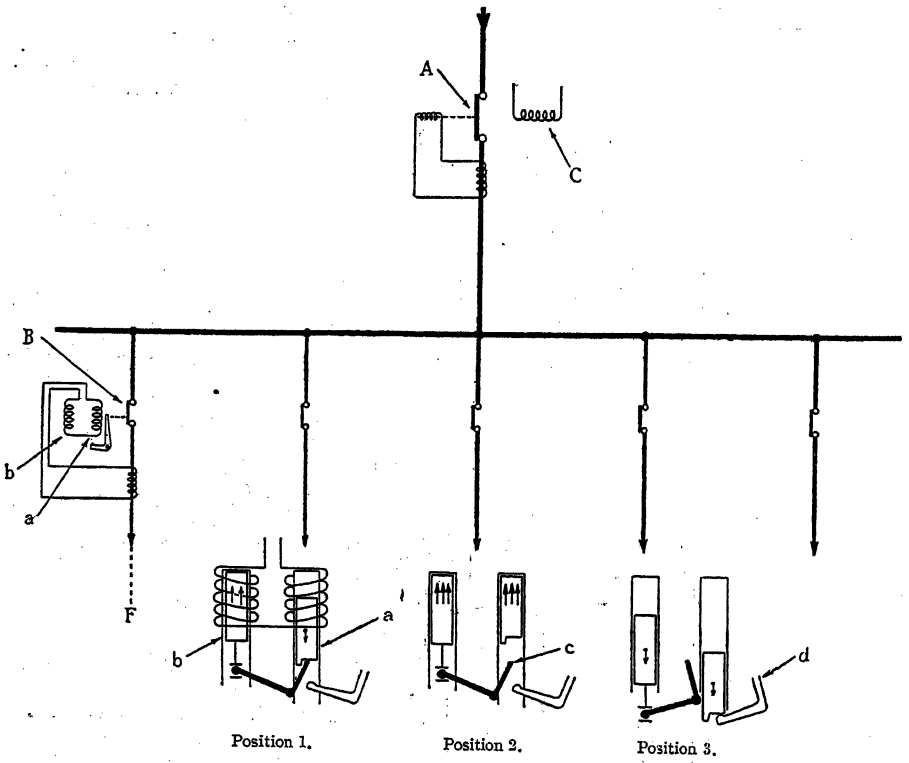


FIG. 46.—Principle of sequential group-switching (necessary time-limit elements omitted for simplicity).

a.—Over-current coil and plunger.
b.—Under-current coil and plunger.
Position 1.—Normal condition. Plungers "a" and "b" are interlocked mechanically.
Position 2.—On a fault at F, plunger "a" is lifted, and both plungers are held up until main fault current ceases, i.e. until group circuit-breaker A opens on self-contained over-current release.
Position 3.—Plunger "b," in falling, removes interlock "c" from path of plunger "a," which falls on tripping-arm "d" and trips feeder circuit-breaker B.
Group circuit-breaker A recloses automatically by coil C after a short interval.
On healthy feeders, plungers "a" and "b" remain interlocked as in position 1.

(xx) Fault-Current Limitation.

The need for care in the lay-out of circuits in its effect on the selection of switchgear has become more and more obvious with the continued growth of systems; and reactors are being used to an increasing extent in order to limit the consequences of short-circuits, and to minimize as far as possible the size of the switchgear required for any given network. To obtain metal-clad construction of reactors, methods have been tried out using windings consisting of single or multi-core cables on a concrete former; but the enclosure of suitably screened coils in oil-filled tanks, following transformer practice, is proving more economical. Fig. 49 illus-

trates a novel combination of switchgear with reactance in feeder circuits. Incidentally, it also shows the

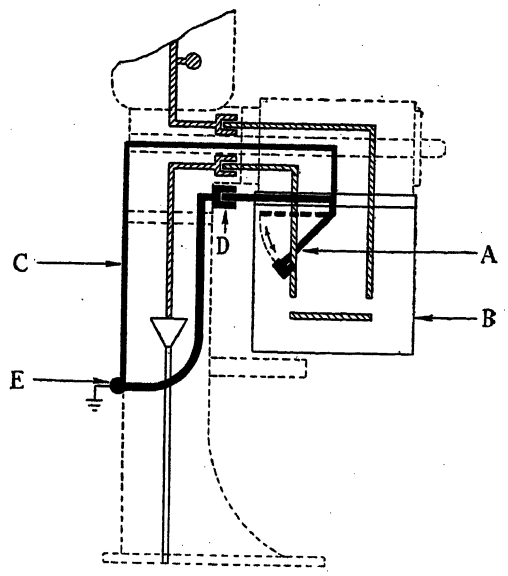


FIG. 47.

A.—Earthing-switch blade in " on " position. Handle interlocked with circuit-breaker handle and rack-out gear so that it is impossible:
(1) To close A before B is " off."
(2) To close B before A is " off."
(3) To rack out when A is " on."
B.—Circuit breaker with usual interlocks and additional interlock with A.
C.—Normal earth-circuit through framework.
D.—Supplementary earth-circuit through plug contacts.
E.—Earth bar.

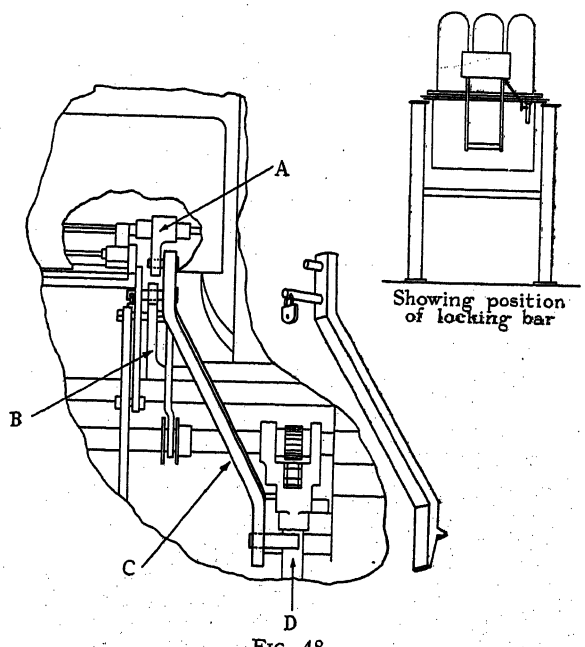


FIG. 48.

A.—Moving part of circuit-breaker mechanism.
B.—Framework.
C.—Locking bar.
D.—Racking-out lever.

alternative switching method of earthing the feeder cable referred to in the immediately preceding paragraph.

Further, while considering metal-clad auxiliary equipment it is interesting to note the revival of liquid resistors for use in earthing the neutral point of high-voltage systems. The employment of metal-covered cables in this circuit permits the application of metal-clad principles in a simpler manner than is possible with any other form of earthing resistance. The negative temperature-coefficient of the liquid operates in the direction of providing a " current-growing " effect when earth-fault currents are passing.

(xxi) Tripping Batteries.

An advantageous change in the type of battery in common use for substations has been made. Primary batteries of Leclanché cells have been found wanting,

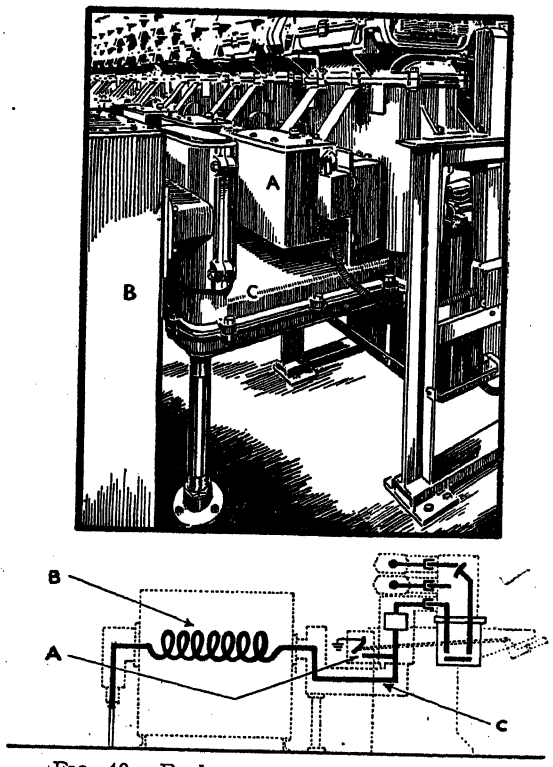


FIG. 49.—Feeder reactance and switchgear.

A.—Earthing switch.
B.—Metal-clad reactance.
C.—Trunking for connections between switchgear and reactance.

owing, for example, to corrosion of terminals requiring excessive maintenance in cleaning, breakage of jars, excessive creepage, and evaporation of the electrolyte. The labour involved in periodic inspection and overhaul has justified a preference for secondary batteries of the nickel-cadmium type, which incidentally are more in conformity with the principles of metal enclosure, and for that reason effect economy in space and maintenance cost. The " trickle " charging of tripping batteries is now a point worthy of attention, particularly for large sizes, which cannot be conveniently transported to a charging station.

(3) AUTOMATIC ISOLATION OF FAULTS.

(i) General.

In no period of the history of automatic protection has the quest for change in design been so active. The

increased length and importance of lines introduced by the British grid have made the need for stability still more pronounced, and the technical difficulties more acute. In the same connection, the reduction in cost of pilots in discriminative feeder-protective systems, or their total elimination, has been insistently called for by the Central Electricity Board in its exercise of economy.

Attention was first paid to the perfecting of the established balance (Merz-Price) systems, and several detail corrections made these acceptable, but only for short lines on account of the high cost of long pilot cables. Then came the time/distance system, with a study of the earlier impedance types and the later reactance types, concentrating upon the reduction of time in operation in order to approach the quality of the balance systems. In the meanwhile, consideration of the possibility of cheapening the pilots for balance systems helped to evolve systems using the inter-operation of relays by means of signals that could be passed over channels used for telephony, or by means of high-frequency currents superimposed on overhead lines. Recent thought has been in the direction of quickening the action of protective gear between the occurrence of a fault and the isolation of the faulty section, on lines of any length, with the use of a practically costless pilot, and without sacrifice of stability.

Protective systems operating in the minimum possible time are referred to as " instantaneous," although the description can never be strictly correct, because a relay requires time even to energize it, apart from the time taken to operate it. It implies that the action of the protective system is such as to start the operation of the trip mechanism of the circuit breaker without deliberate delay. The ideal system would be truly instantaneous, and in addition, to be perfect for universal application, should be a unit system; that is to say, its operation and discrimination on any one section of the network should be independent of the operation and discrimination on any other section, so that the network may be extensible in any way, with tees as well as with loops, without interference with any existing equipment.

The interlinking of power stations and systems is now on so large a scale that a possible reduction of circuit-breaker stresses in dealing with short-circuits has sometimes been suggested by means of automatic sectionalizing prior to the clearance of the line on which the fault exists. Time-limit over-current releases have always been required at power stations and other crucial feeding-points, as a precaution against failure of the switchgear or of the discriminating protective equipment, which constitutes a busbar fault; and the application of these at an additional number of points is preferable to sectionalizing into blocks interconnected by circuit breakers with over-current releases between sections of the network, on account of the dislocation that would be caused by the too frequent unlinking of plant or network, with possible difficulty in subsequent recoupling.

Even with the best of discriminative protective systems, " back-up " protection will always be required, because of the risk of a circuit breaker failing to clear although the protective system has initiated its operation correctly. Moreover, the zone covered by the protective system does not usually include the busbars or the transformers themselves. The transference of operation from one relay to adjacent relays with an additional time-delay in the event of a circuit-breaker emergency has been proposed; and balance or leakage protection has been used to clear all circuits connected to a busbar fault; but neither of these by itself is a complete solution. When complete back-up and busbar-fault protection is regarded as essential, it can be best secured by the addition at all feeding-points of time-limit over-current releases, preferably of the inverse-current type, with low definite minimum time-settings.

Of the classes described in Section (3)(iii) below, the balance class contains the best examples of technically ideal unit systems; the self-balance class also includes unit systems; the unit systems of the direction class have a limitation in respect of adjustments when adding tees to feeders; and the time class, although not completely of the unit type, has the inherent advantage of providing back-up and busbar protection, since operation in adjacent sections overlaps, with time-discrimination.

(ii) Limitation of Damage.

The ideal of instantaneous isolation of faults has been generally accepted. Formerly, long time-limits were adopted in some quarters as a means of discriminating, but now it is realized that the original North-East Coast practice of maximum speed of fault-clearance is essential for restriction of damage as well as for continuity of supply. The tendency is to think in terms of the minimum number of cycles required to clear a fault from its start to the interruption of the arc in the circuit breaker; that is to say, during

(1) The operation of the relay.
(2) The energizing of the trip-coil.
(3) The movement of the circuit-breaker parts up to the point of separation of the sparking contacts.
(4) The arcing period before extinction.

For example, on a 33 000-volt network, with an instantaneous protective system, it should be possible to clear a fault in 8 cycles. The various forms of protection have to be judged by whatever number of cycles their delayed-action characteristic adds to this period.

As a further aid to the limitation of damage by the use of instantaneous protective gear, the operation of the alternator field-switch* is an important addition, the object being to prevent the spread of burning of armature windings and cores after the occurrence of a fault. This has justified the practice of making the field switch (which takes the form of a direct-current circuit breaker) operate instantaneously, without a discharge resistance, immediately after the initial movement of the main circuit-breaker. For similar reasons, the neutral earth-connections are opened automatically by simultaneous operation of the alternator neutral-earthing switch.

(iii) Present-Day Practice.

Selective protective systems for fault isolation may now be divided into four generic classes according to the way in which they provide discrimination, namely:

(1) Balance; (2) Time; (3) Self-balance; (4) Direction.

Systems for generator and transformer protection fall

* *Journal I.E.E.*, 1925, vol. 63, p. 445, Fig. 36.

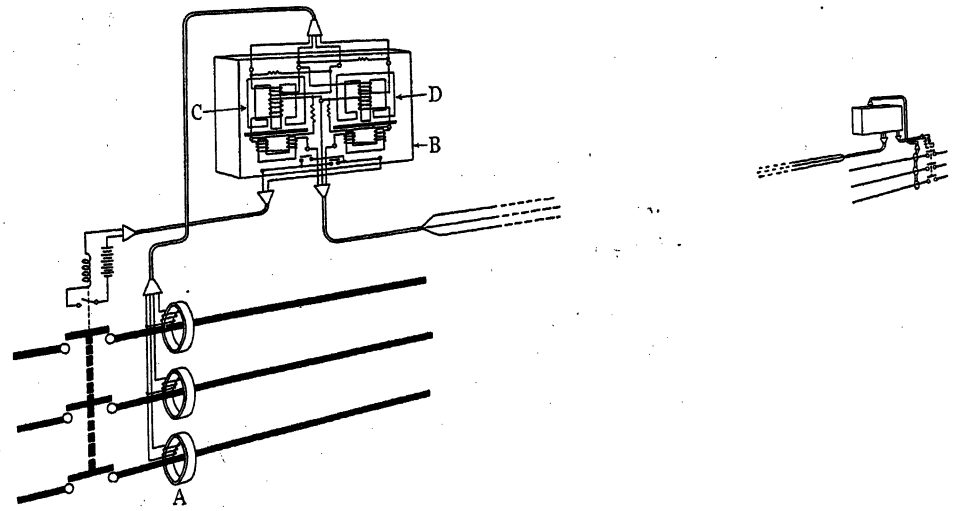


FIG. 50.

A.—Current transformers.
B.—Double-element rotary relay.
C.—Phase-fault windings.
D.—Earth-fault windings.

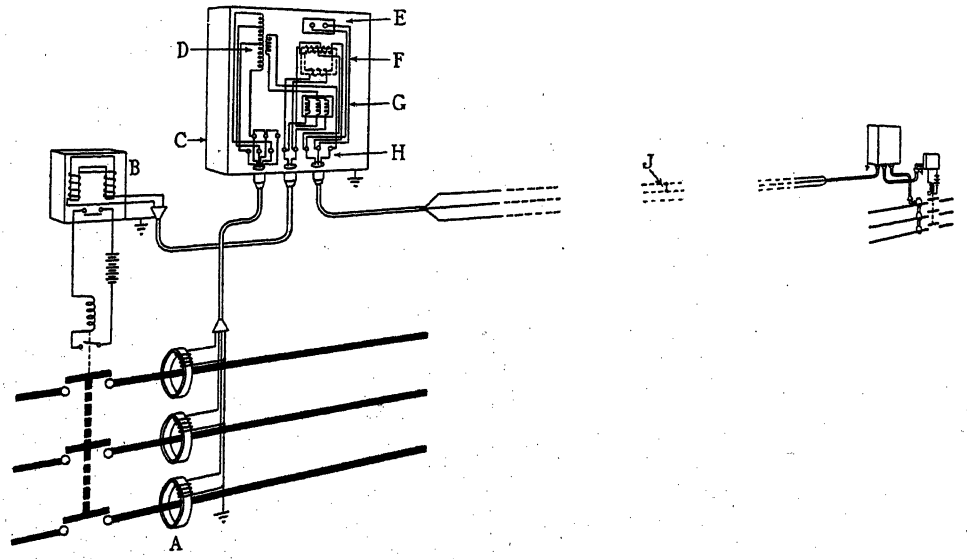


FIG. 51.

A.—Solid-core current transformers.
B.—Single-pole relay.
C.—Metal case.
D.—Summation transformer.
E.—Tuning condenser for ensuring oscillatory stability.
F.—Split-pilot transformer.
G.—Divertor reactor.
H.—Terminal block, including central testing point.
J.—Mid-point tripping connection.

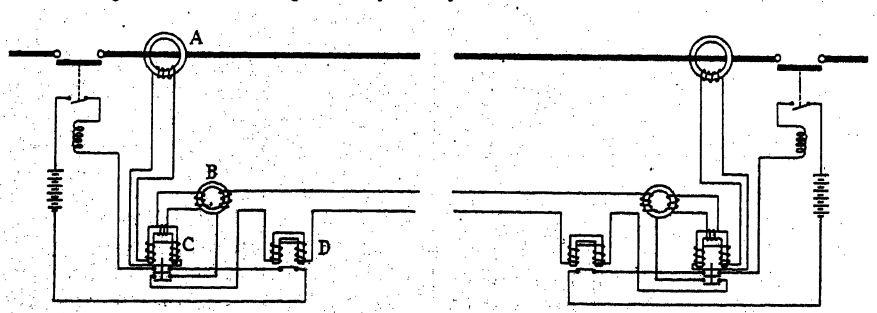


FIG. 52.

A.—Balance-type current transformer.
B.—Saturable current transformer.
C.—Overcurrent-relay transformer.
D.—Circuit relay which (*a*) opens the trip circuit and prevents tripping on a " through " fault, and (*b*) remains inert and allows tripping on an internal fault.

chiefly into the first class, and have met modern conditions with little, if any, fundamental change. On the other hand, feeder-protective systems have been changed in general character to meet modern requirements of economy, which have already been mentioned, and are dealt with in further detail below.

(1) *Balance.*—All types of balance protection depend upon the use of a pilot or channel of communication used in the form of a pilot cable or a telephone pair, and are derived from the Merz-Price type of protective systems. This widely-used class includes the McColl bias, the "translay," and the split-pilot systems.* The progress in these has been mainly effective in securing greater stability on the occurrence of "through" faults, in the first-mentioned system by bias opposition in the tripping relay, in the second by eliminating the effects of pilot-wire capacitance currents by adjustment of the field in an induction-type rotary relay combined with a transformer (Fig. 50), and in the third by neutralizing the effect of capacitance, vagabond, and other harmful currents by the use of the conductors in the pilot cable on the split-conductor principle of self-balance, thus operating with plain electromagnetic relays (Fig. 51). In the last-mentioned system, further, a tuning arrangement is used to prevent inadvertent operation of the relays by currents of abnormal frequency.

Another system,† starting on new ground, has for its basis the balance, up to certain limits, of current transformers with a low saturation-point (Fig. 52). Tripping is by overload relays interlocked through a pilot wire. The condition for stability on "through" currents in sound sections is that the sum of the currents circulating in the pilot wires operates lock-out relays, which prevent tripping; but in the faulty section the difference of the currents, now in opposition, is insufficient to operate the lock-out relays, and thus the overload relays are allowed to bring about tripping. The advantage of this system is that the pilot voltage is restricted to a low value, and there is a possible saving in first cost on this account.

A proposal‡ has been fully explored to replace the pilot cable with a telephone pair, by which the secondary currents converted into direct currents through small rectifiers at each end of the feeder would be balanced; but since in the conversion the direction of the power flow in the feeder was not reflected by the direct current in the pilot wire, the system was inoperative for a fault fed by equal currents from both ends of the line. In its simplest form it was like the parent Merz-Price system in having no voltage transformer. It also provided instantaneous operation and, in addition, it could be used with a cheaper form of pilot, such as a telephone pair.

For accuracy in operation and minimum time-function, the balance class remains the nearest approach to the present-day ideal for instantaneous operation. Its main virtues are that it functions on current alone, and that it is a simple and flexible unit system.

(2) *Time.*—The types of protective systems in the time class emanate from serial and graded pilotless time-discriminating devices, of which the fuse is a primitive example. During the period under review the types known as distance-relay systems, using restricted time-discrimination aided by a sense both of direction of power flow and of the distance of the fault from the relay, have progressed, mainly on account of the long lines of the British grid, to the extent that now, for 132 000-volt lines of 12 miles in length and over, the characteristics are nearly equal to those of the balance class in speed of operation. The impedance system and the ratio-balance system* are modern systems in this class. Such systems provide discrimination by automatically controlling the time-delay in accordance with the distance of the fault from the relay, as measured, for example, by the impedance of an earth-fault loop in the impedance system, and by the reactance of an earth-fault loop in the ratio-balance system.

Experiments with open arcs have proved that, owing to the inconsistency and variation in the resistance of an arcing fault, impedance measurement may lead to incorrect location of the fault, with consequent isolation of the wrong section, whereas by eliminating the resistance component in the relay design a reactance measurement is obtained by which the risk is removed (see Appendix III). The technical limitations imposed by time-grading put this class at a disadvantage when compared with the balance class; but on the other hand the entire elimination of the pilot compensates liberally for its lack of simplicity, which in essence is due to the addition of a voltage element for direction and distance detection, and other auxiliary selective devices.

(3) *Self-balance.*—In this class, the pairing of cables, or of conductors, provides the means of fault discrimination. Types still in use are split-conductor protection, using two cores for each phase or two separate 3-phase cables or lines in parallel with the conductors grouped in pairs, and 4-core protection, in which only one phase is paired. They depend for operation upon the inequality of current in the conductors of a pair caused by a fault. Where the use of two cables or lines in parallel is not impracticable for other reasons, protection is secured for a negligible extra cost.† The principal problem originally encountered was to ensure tripping at the feed end of the protected line with a fault at the far end. This was solved by using an expensive reactance-type current transformer with an ordinary circuit breaker, and later by using a split-conductor circuit breaker with single-turn current transformers. A recent solution adds a pilot in the form of a telephone pair, which enables an ordinary switch to be used‡ (Fig. 53). The pilot thus takes over the function both of the reactance-type transformers and of the special circuit breaker with split conductors. The use of tees off main cables is frequently a handicap to protective systems. Split-conductor protection can be adapted to a tee-off in the way shown in Fig. 54, in which a differential reactance bridges the splits, and the consumer's load is protected by a switch-fuse. The self-balance class operates only on current, and in this respect ranks with balance protection for simplicity. The systems it includes are also unit systems.

* *Journal I.E.E.*, 1930, vol. 68, p. 828; also B. H. Leeson and H. Leben: "The Principles of Feeder Protection and their Application to Three Modern Systems," Paper No. 106, presented to the International E.H.T. Conference (Paris), 1931.
† Biles, Satralock protection.
‡ J. R. Beard.

* *Journal I.E.E.*, 1930, vol. 68, p. 832; also B. H. Leeson and H. Leben: Paper No. 106, presented to the International E.H.T. Conference (Paris), 1931.
† *Journal I.E.E.*, 1925, vol. 63, p. 443.
‡ Gripper.

(4) *Direction.*—Apart from parallel-feeder protection using directional relays, the entire progress in this class has been recent. A system was proposed at one time* for the protection of an interconnector between two power stations, but since isolation of the fault depended upon fault current being fed from both ends simultaneously, and at that time reverse-power relays were not up to present-day standards of reliability, it made no progress. A lock-out scheme† was proposed long after for overlapping operation on a chain of feeders, but it has not found favour owing to its being a non-unit system. This and other later systems in the direction class obtain discrimination by the transmission of a signal over a pilot.

The interlock‡ system (Fig. 55) was developed to provide unit protection and to enable the signals required for discrimination to be transmitted over any form of pilot. The tripping of the circuit breakers is prevented by the lock-out signal transmitted individually in each section that carries a "through" overload or earth-leakage current, first consideration being given to stability. No signals are sent on the faulty sections, and hence the circuit breakers on these are allowed to operate as soon as the sound sections are stabilized.

To effect further economy, the system was so designed that if, for example, a telephone pair were used normally for telephony or control it could be borrowed momentarily for transmitting the signals during the existence of the fault on the protected feeder, after which it would be restored to its normal use. By this innovation an important step in design was made towards the elimination of a separate pilot for protection alone: an answer was given to the demand for pilot economy by producing a workable system with a practically costless pilot.*

Another variety of this form of protection was subsequently evolved,† in which the relays transmit, in a manner similar to the established duplex telegraphy, dual signals for stabilizing the lines carrying "through" fault currents, whereas the balance of the signals at the ends of the faulty line allows tripping of the circuit

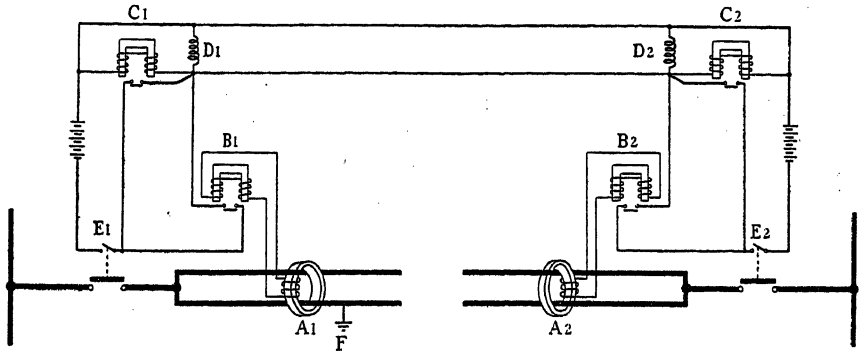


FIG. 53.

A1 and A2.—Split-conductor current transformers.
B1 and B2.—Overload relays.
C1 and C2.—Pilot relays.
D1 and D2.—Trip coils.
E1 and E2.—Circuit-breaker auxiliary switches.

Sequence of operations on the occurrence of a fault at F:—
Relay B1 operates, and energizes trip coil D1 through switch E1, thus opening the circuit breaker. Relay C2, being in parallel with trip coil D1, operates simultaneously, thus energizing trip coil D1 through switch E2.

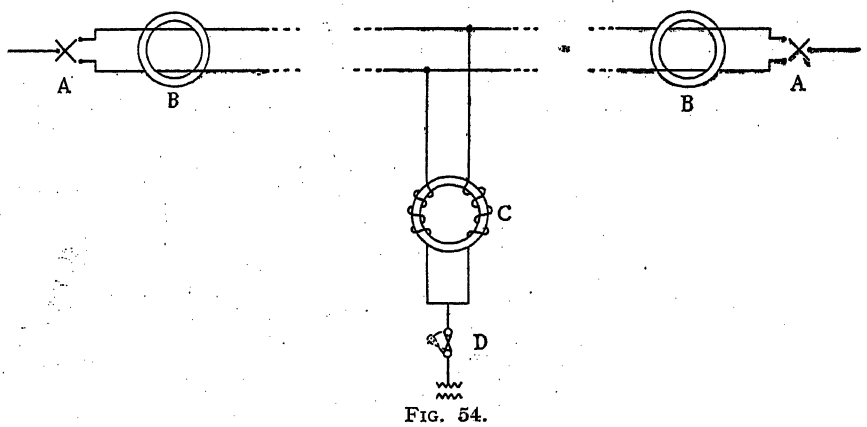


FIG. 54.

A.—Split-contact circuit breakers.
B.—Split-conductor current transformers.
C.—High-impedance reactor.
D.—Switch-fuse.

* Garrard, 1908.
† Longfield.
‡ *Journal I.E.E.*, 1930, vol. 68, p. 832; also B. H. LEESON and H. LEBEN: Paper No. 106, presented to the International E.H.T. Conference (Paris), 1931.

* Scott and Leeson. † Kapp and Carrothers.

breakers. This method is an interesting and novel application of a well-known system of signalling, and may prove to have its advantages in that it includes sequential functioning of relays for faults fed from both ends, thus speeding up the operation on faults of this type; but the means of transmitting the signals would appear to confine its application to pilot-wire working. In one form, the pilot wire is embedded in the core of the earthed guard-wire to effect economy.

A reduction in the operating times of these protective

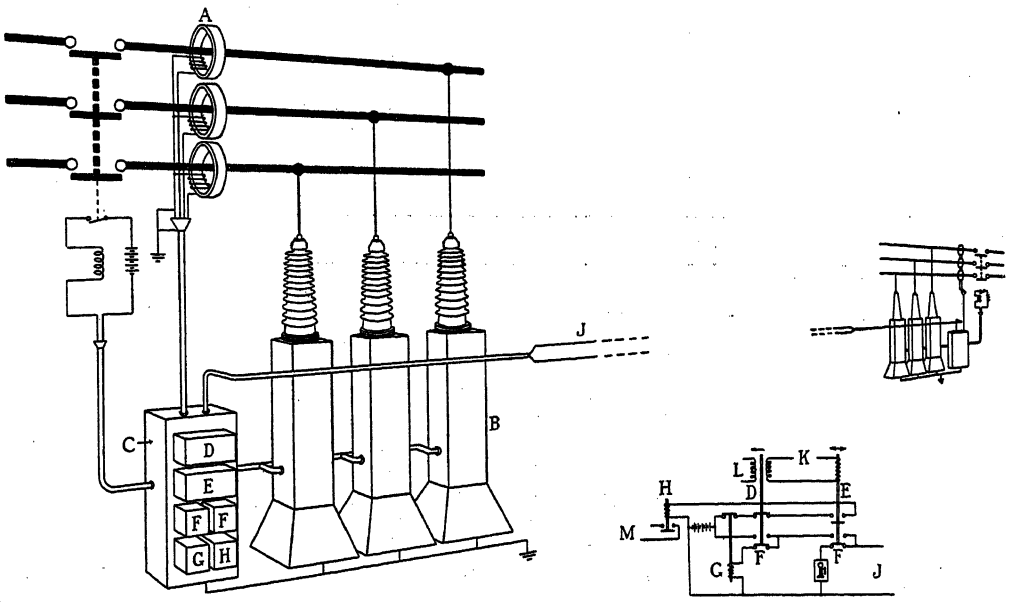


FIG. 55.

A.—Solid-core current transformers.
B.—Condenser coupler for voltage supply to directional relays.
C.—Relay cubicle.
D.—Directional stabilizing relay.
E.—Overcurrent and earth-leakage tripping-relay.
F.—Change-over relays for bringing pilots into circuit.
G.—Lock-out relay.
H.—Time-margin tripping-relay.
J.—Pilot, which in ordinary service may be used for telephony.
K.—Leads from current transformers.
L.—Leads from condenser coupler.
M.—Leads to circuit-breaker trip coil.

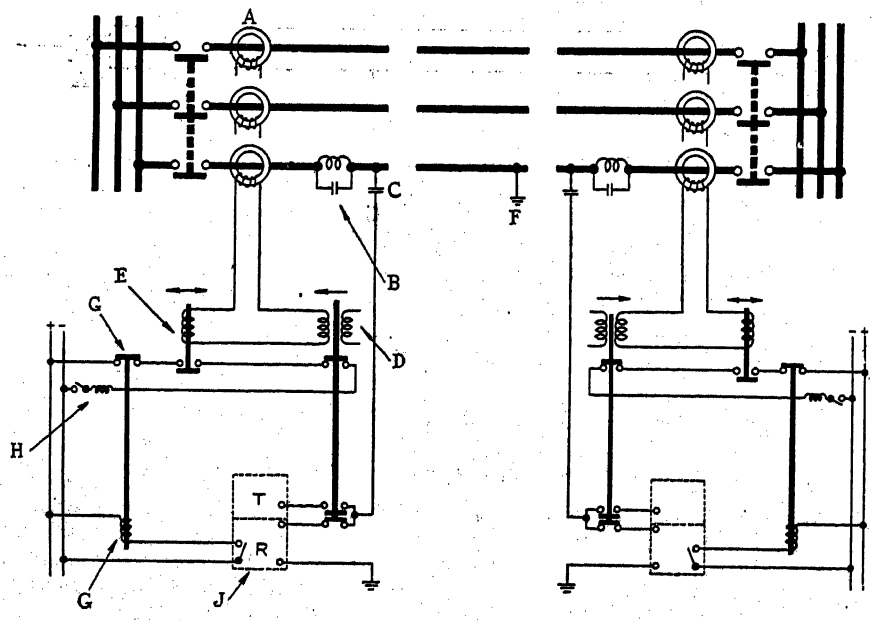


FIG. 56.

A.—Current transformers.
B.—High-frequency choke.
C.—Condenser coupler.
D.—Directional stabilizing elements.
E.—Overcurrent tripping-element with time-margin.
F.—Fault.
G.—Lock-out relay.
H.—Trip coil.
J.—High-frequency transmitter and receiver.
R.—High-frequency receiving apparatus.
T.—High-frequency transmitting apparatus.

systems when applied to networks would be a desirable advance towards the ideal of instantaneous protection; but it should not be made by taking a risk in cutting down the time-margin required to secure correct sequence of locking and tripping.

The method of employing superimposed high-frequency current over the power line as the pilot for an interlock system, which is now established in British practice, is shown in simplified diagram form in Fig. 56. The use of a uniform definite time-margin provides the necessary

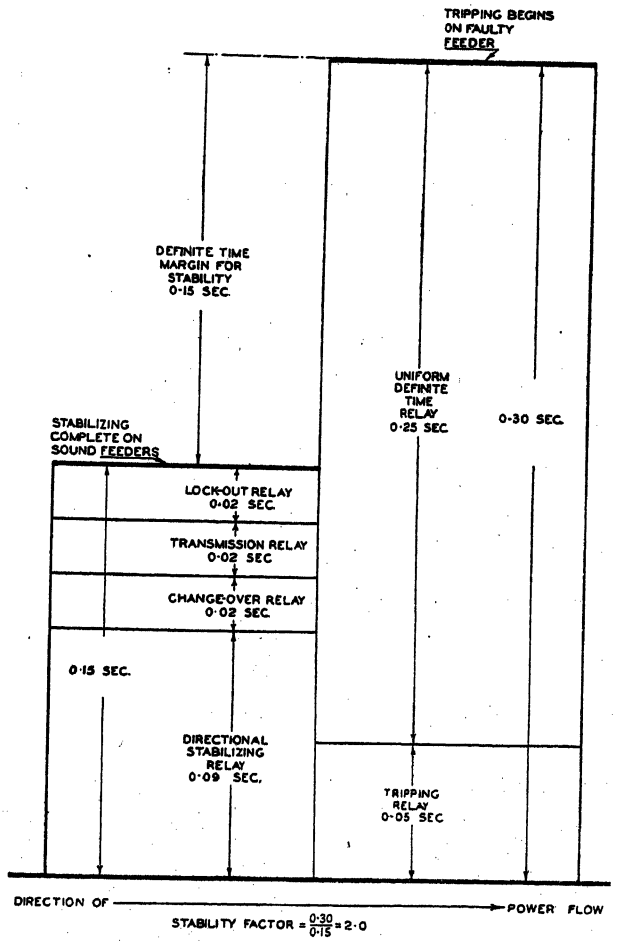


FIG. 57.—Stability diagram of superimposed interlock protective system.

stability by locking out the sound feeder prior to tripping the faulty feeder (Fig. 57). Since operation takes place without the passage of a signal over the faulty section, a breakage of a line does not interfere with the normal operation of the protective system.

The directional class, in general, suffers like the balance class in requiring a pilot, and like the modern time class in requiring voltage elements for direction-detection; but on the whole, in economy, it lies between the two classes, because the voltage element may be disregarded relatively to the pilot, and the pilot itself is, at the most, inexpensive when used in one or other of the phantom forms described. Interlock systems of this class go a long way towards reaching the ideal; and, given a directional element to function on current only, the operating merits of the Merz-Price system would be obtained without the cost of pilot wires.

(iv) Safeguarding Telephone Systems.

A new item not included in the recently-reviewed problem of interference between power and communication circuits* arises out of the introduction into protective systems, and also into the remote-control systems referred to later, of telephone pairs and channels, which thus become electrically associated with the power lines through voltage transformers, current transformers, and earthing network. A failure of insulation on the transformers, which is a rare occurrence, directly raises the potential of the secondary circuits, but in addition, when an earth fault develops in this or any other part of the power circuits, momentary potential differences are set up because of the resistance of the earth-return path, and this also raises the potential at some part of the telephone-cable sheath above that of the enclosed

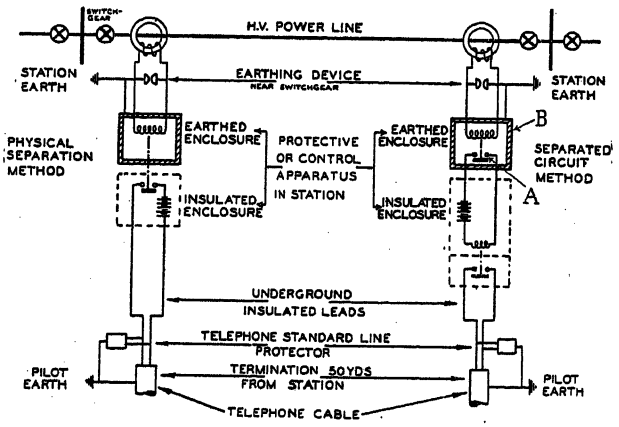


FIG. 58.

For explanation of A and B, see Appendix IV (page 329).

conductors, the amount being dependent upon the proximity of the sheath to the main earth-circuit of the power system. Research on these possibilities, carried out by means of a test plant with fault currents simulating service conditions, has proved that definite precautions are necessary for ensuring safety and non-interference with telephone service (see Appendix IV). These are indicated diagrammatically in Fig. 58, and involve the use of separate earthing-devices for the secondary circuit and, as further safeguards, either "physical separation" or a "separated circuit" in the association between the secondary circuit and the telephone cable, and a separation of the telephone cable earth from the main earth-plates of the power network.

(4) REMOTE AND AUTOMATIC CONTROL.

(i) General.

Now that large areas are dependent for their most efficient supply on a properly controlled division of load between generating units, which are whole power stations instead of single generators, some means is essential of focusing at a central point in an easily

* W. G. RADLEY: *Journal I.E.E.*, 1931, vol. 69, p. 1117.

visible way all the information required to enable the controlling staff to issue general directions to the several units concerned, and actually also to initiate such switching and other major operations as are required from time to time by changing conditions of consumption.

The remote control of switchgear, although it was primarily adopted for convenience in control on account of the compact assembly of the operating switches and instruments, acts as a safety feature also. The safety feature may be extended to promote maintenance of supply by the further development of remote control and the addition of automatic control, in virtue of its acting as a substitute for human thought through operative functions definitely predetermined to correspond to preconceived occurrences.

It was stated* in 1924 that "no system appears to have been constructed taking full advantage of all the means available, i.e. using discriminating protection in combination with automatic indication and code signalling, and it is probably a matter for satisfaction that this possibility of improved working is in reserve and available to meet the more onerous conditions towards which electrical developments appear to be moving. . . . We may expect to see systems in the future more extensive in area and dealing with much larger loads than anything now contemplated. Successfully to control such systems will probably require, in the completest combination, all practicable safeguards known to the present-day electrical engineer."

The time foreshadowed is now upon us, but we have yet to put to their full use all the known combinations of control, indication, and protection. There are, however, instances of partial steps towards the fulfilment of this prophetic statement, sufficient in themselves to justify an attempt to predict the state of practice in another decade.

* P. V. Hunter: "Control and Switching of High-Pressure Distribution Systems," abstract of paper read before the Société Française des Electriciens, *Electrical Review*, 1924, vol. 94, pp. 72 and 118.

The progress of the automatic control of substations has led to other remote and automatic control schemes of great importance, such as automatic synchronizing of generating plant and automatic frequency-control with load-sharing; and these, in a centralized form, are now fully practicable. The problems dealt with during the past seven years, like those of protective gear, have been made more pressing by the requirements of the British grid; and again the type of control equipment used is governed by the pilot or the means of communication available.

(ii) Power-station Control Boards.

A typical control board for a large power station, with its operating diagram, is shown in Fig. 59 (Plate 1). The apparatus in the middle of the foreground is for the remote control of the generators, and at the sides for that of the auxiliary equipment.

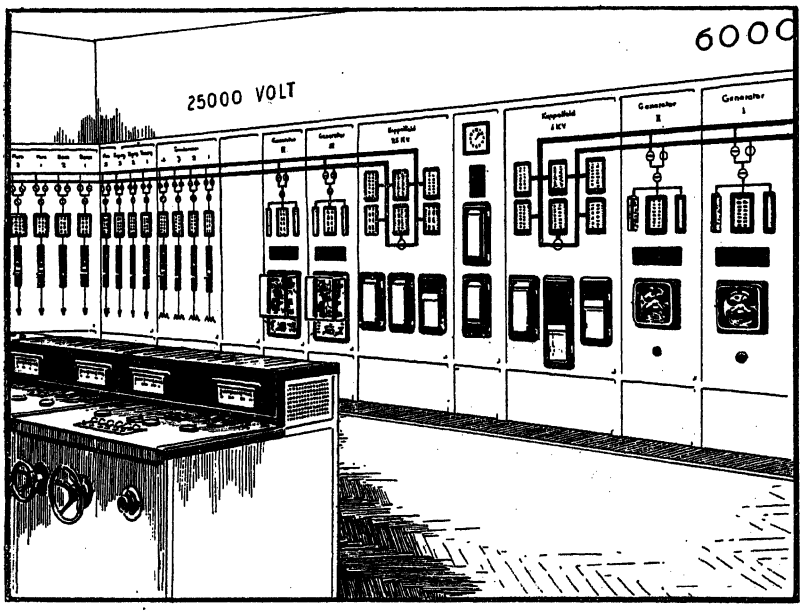


Fig. 60.

Much attention has been given to the neatness of control boards, and particularly to diagrammatic indication and instruments. An example of Continental practice is shown in Fig. 60. The lining-up of a "light-band" on a flat profile-type instrument is effected by having a scale of ground glass illuminated by a small lamp. The light is obscured by a blind, which moves according to the amount of current through the coil. The instruments form part of the diagram, and are uniformly calibrated so that a glance shows an area of light that affords a measure of the total load.

This leads up to a control board as shown in Fig. 61, on which the several circuit breakers, and possibly the isolating features also, are operated by keys situated in the diagram lines and mounted in a sloping circular plane just below the indicating instruments. Relays and recording instruments, which need only occasional inspection, are mounted at the back, with an intervening space forming a well-lighted passage-way and giving access to the wiring, terminal boards, and cable boxes.

In this way the control engineer has only the essential operating features before him, and this simplification allows concentration upon vital issues. A further aid is the use of superimposed system-diagrams embodying the new feature known as premeditated switching (Fig. 62). This enables the control engineer, by the operation of keys, to rehearse on the diagram the switching operations he intends to carry out, and as he does this the differences between the contemplated changes and the actual conditions are recorded on the diagram. Having satisfied himself that the new switching scheme is correct, he then puts it into practical operation, and in so doing brings about agreement on the diagram between the intended and the actual switching conditions.

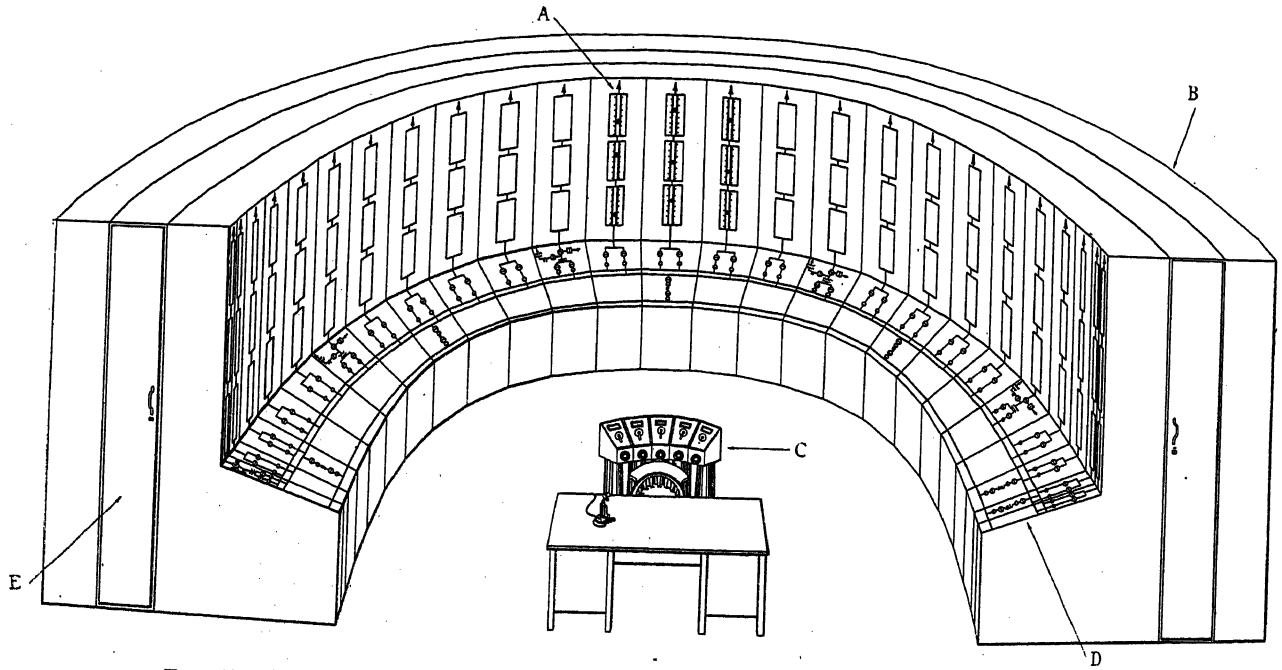


FIG. 61.—System diagram with indicators for premeditated switching and for operative control.

A.—Indicating instruments.
B.—Recording instruments and relays at back.
C.—Generator controls.
D.—Diagrams and operating keys.
E.—Entry to passage-way.

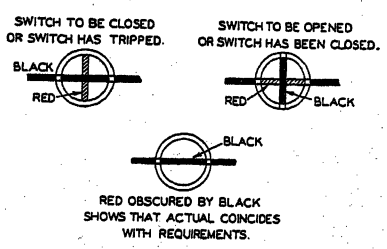


FIG. 62.

A modern control board of this type may include also a diagram of the steam connections, and these connections can be indicated and controlled in the same kind of way as the electrical connections. In one power station,* controls for the boiler fans, dampers, and stoker motors, are arranged on a board together with the steam-valve controls, thereby providing centralized operation of the whole of the extra-high-pressure steam plant. For this installation there is complete desk-control in the e.h.p. turbine room of the 1 100-lb. boiler plant, which is all electrically operated; and although no diagram of the steam connections has actually been incorporated in the control board, such a diagram could readily be added if thought desirable.

* Bradford Corporation.

(iii) Network Control Rooms.

The lay-out of control rooms has afforded scope for much ingenuity in the design of detail parts and of their architectural structure. For example, the old painted diagrams, on which tallies and labels were hung, are replaced by diagrams engraved on metal panels (Fig. 63, Plate 1). Signal lights are operated from a desk keyboard on receipt of information by telephone, and remotely-operated instruments indicate the load distribution continuously. Figs. 64 and 65 show details of the Bennett-system lights and diagrams included in this network control.*

The short-circuit calculator is the latest addition to control-room equipment, and an example is shown in Fig. 66 (Plate 1). It consists of a group diagram representing completely the interlinking of all power stations and distributing points. Each unit of the generating plant, reactances, and network, is represented in miniature by a resistance proportional to the impedance of the actual circuit it represents. The diagram is therefore adjustable to represent any quantity

* London Power Co., Ltd., Ergon House.

of running plant and any condition of premeditated or actual switching. The switching connections are represented by dual-conductor plugs, each circuit being of the dual type in order to enable both earth-fault currents and phase-fault currents to be determined. A complete picture of all connections is seen at a glance, and the short-circuit current that would occur in any vicinity can be read straight off on a portable instrument, which can be plugged in to the position of any of the switches.

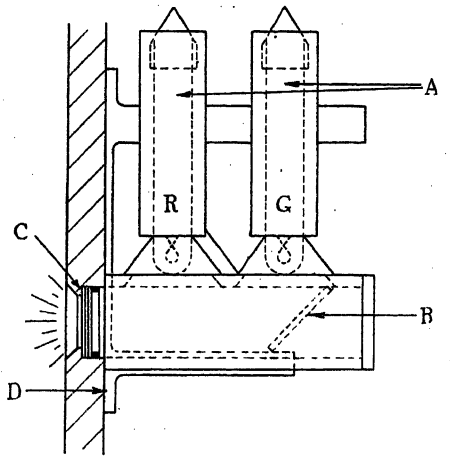


FIG. 64.

A.—Carbon-filament lamp.
B.—Reflector.
C.—Ground glass.
D.—Supporting bracket.
G.—Lamp shining through green glass.
R.—Lamp shining through red glass.

The problem of controlling distribution networks extending over large areas, such as those of the British grid regional schemes, has introduced considerations that have resulted in the adoption of selective control over pilots, and a corresponding elimination of hand-operated indicating and recording apparatus in favour of automatically-operated devices.

A difficulty in using pilots in tandem arises out of the congestion of signals, and they are therefore arranged

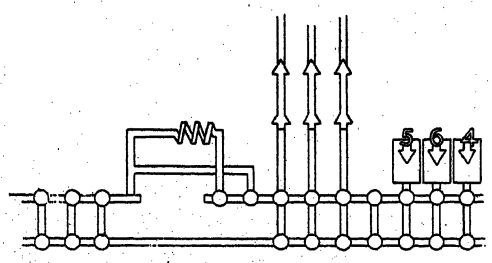


FIG. 65.

radially to ensure immediate indication and flexibility of control. In this system, pilots radiate from the regional control rooms to each of the controlled stations in the area. In the past, the tandem system of pilots has been found suitable for the control of direct-current traction systems, owing to the saving of initial expenditure on pilots; but for the requirements of control of the more vital grid supply the more direct-acting radial system is preferable. To economize in the cost of pilots, Post-Office channels of communication may be used between the control room and the controlled station. Direct current is preferred whenever it is available, but alternating current at audio frequencies may be used as an alternative. A scheme has been developed for places where pilot wires exist already for a balance system of protection, in which the same pilots can be used by the addition of relays to cut in the pilot wire for protective service only when required.

The new requirements have led to the development of equipment that may be divided into two broad classes. The one class uses telephone-relay-type equipment, which has been adapted to meet the modern requirements of plant control; and schemes embodying such apparatus are known as "supervisory control." Trains of impulses

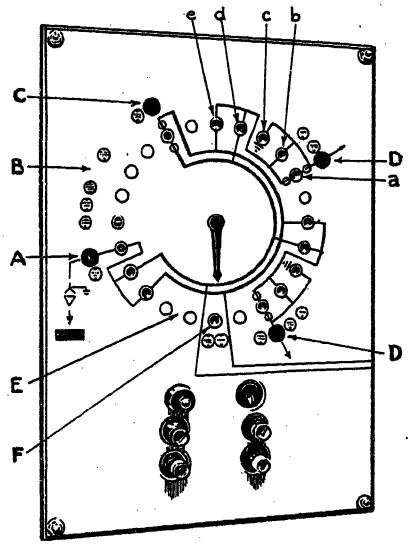


FIG. 67.

A.—Transformer.
B.—Transformer-temperature indication and tap-change indication and operation.
C.—Busbar coupler.
D.—Feeder:—
a.—Circuit breaker.
b.—Bypass isolator.
c.—Earthing switch.
d, e.—Busbar selectors.
E.—Spare ways.
F.—General alarm and telephone (zero position).

are transmitted for the indicating and metering signals, these impulses being received by suitably-adapted telephone-selectors, which in turn operate appropriate relays to control lamp indicators and meters.

The other class of control apparatus centres upon a control dial as shown in Fig. 67, with mechanism more on the lines of switchgear equipment, and the schemes incorporating it are known as "centrovisory control." The principle underlying their development is the replacement of numerous small relays and their electrical circuits by mechanical devices, together with a few robust relays.

The transmission of meter readings is effected by means of a direct-current or alternating-current signal from the controlled station, the duration of the signal corresponding to the time taken for a pointer driven by a timing device to traverse a distance from a fixed zero-point to the position of the pointer on the measuring instrument.

To face page 316.

Plate 1.

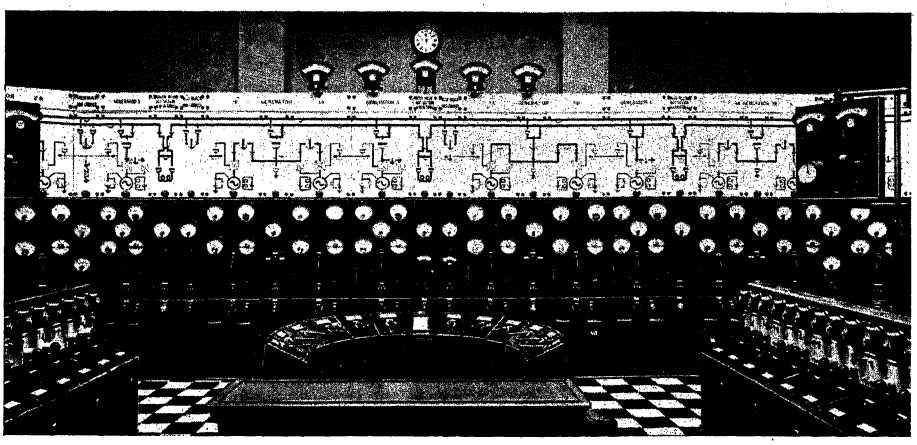


FIG. 59.



FIG. 63.

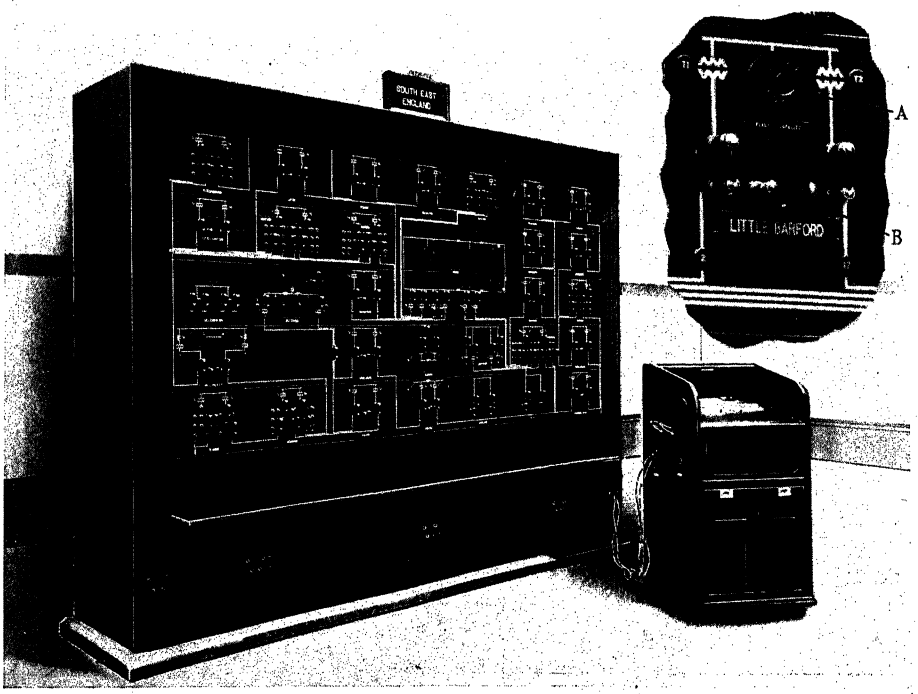
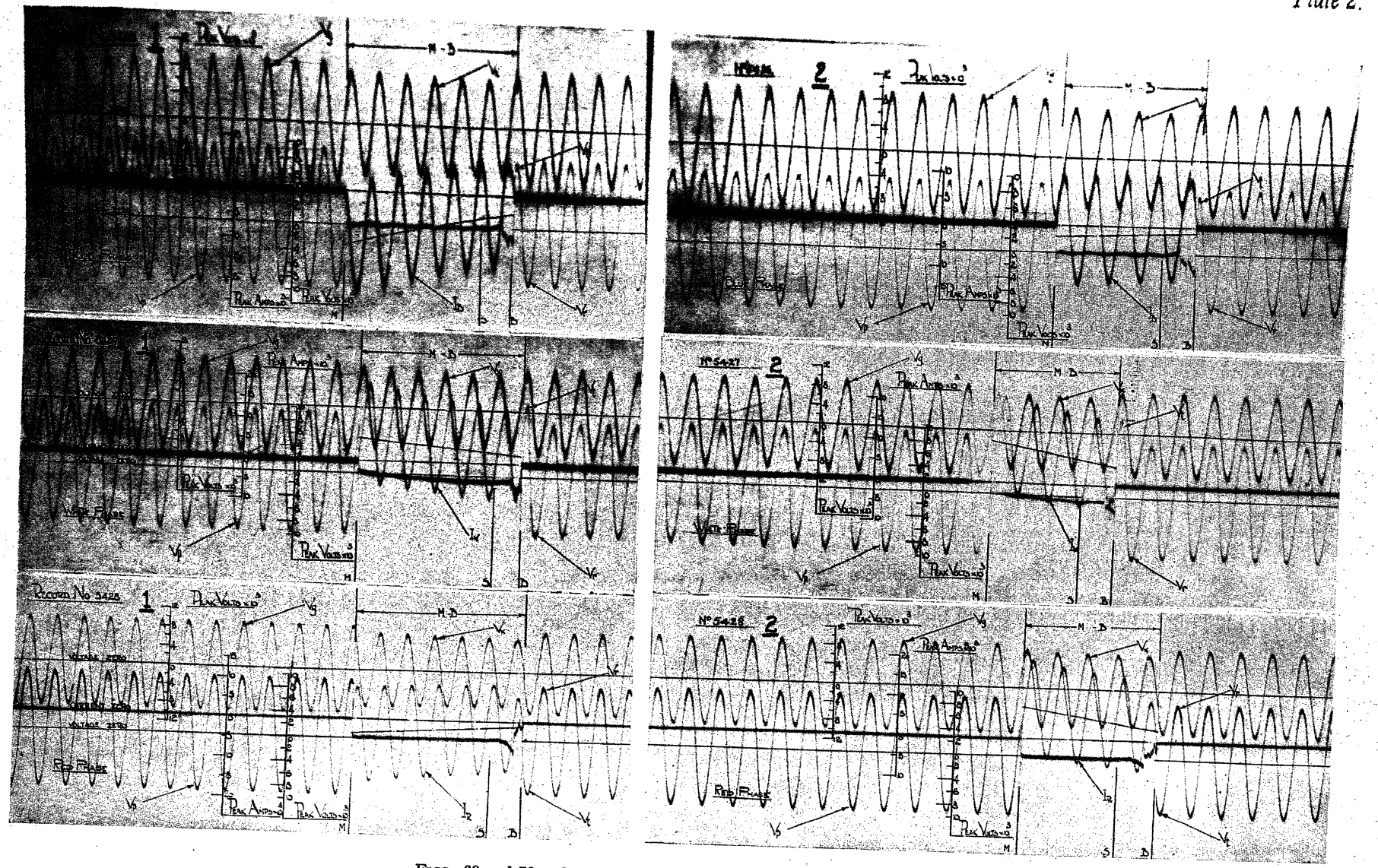


FIG. 66.

A.—Representing generators.

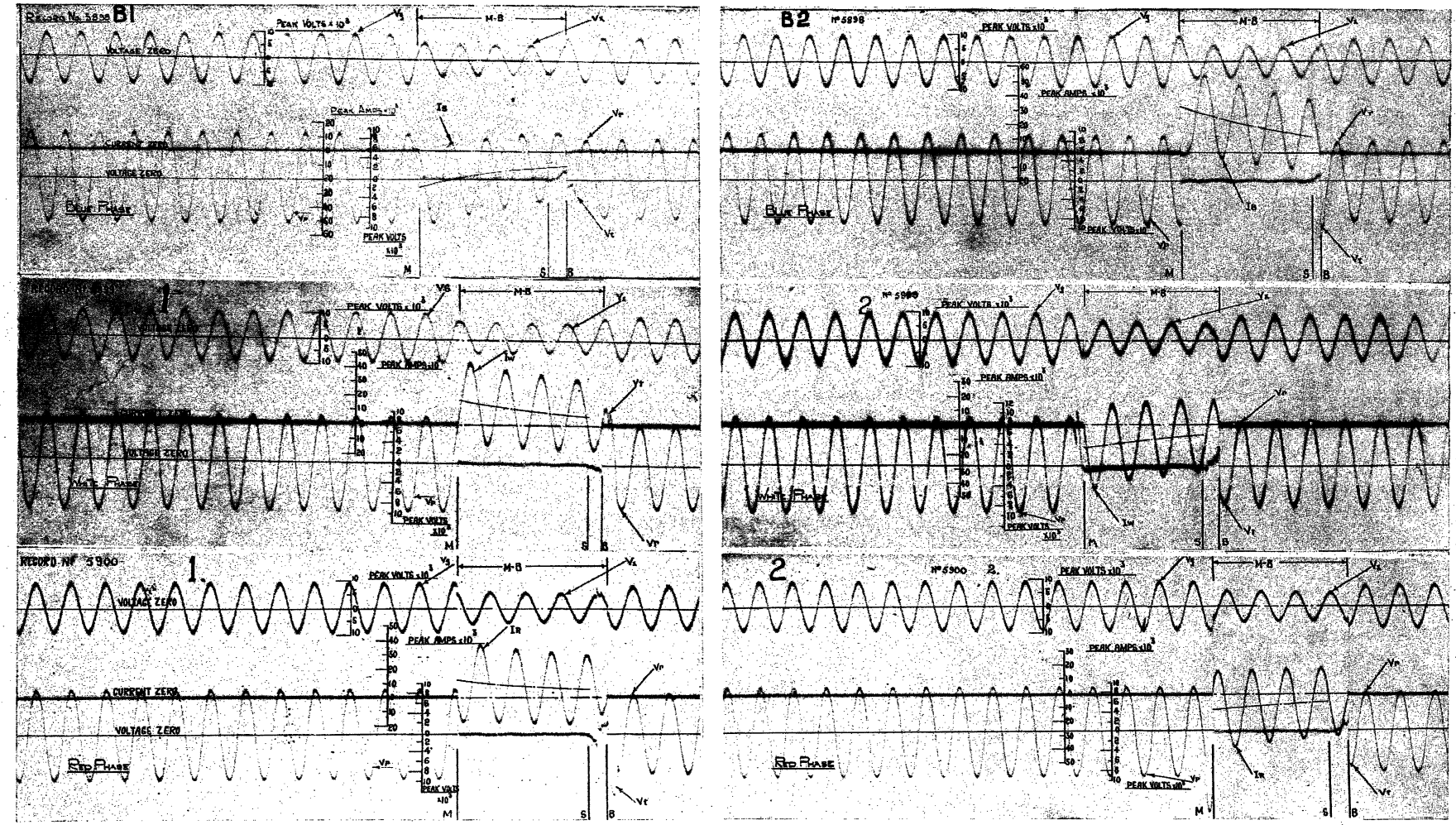
B.—Representing switches.



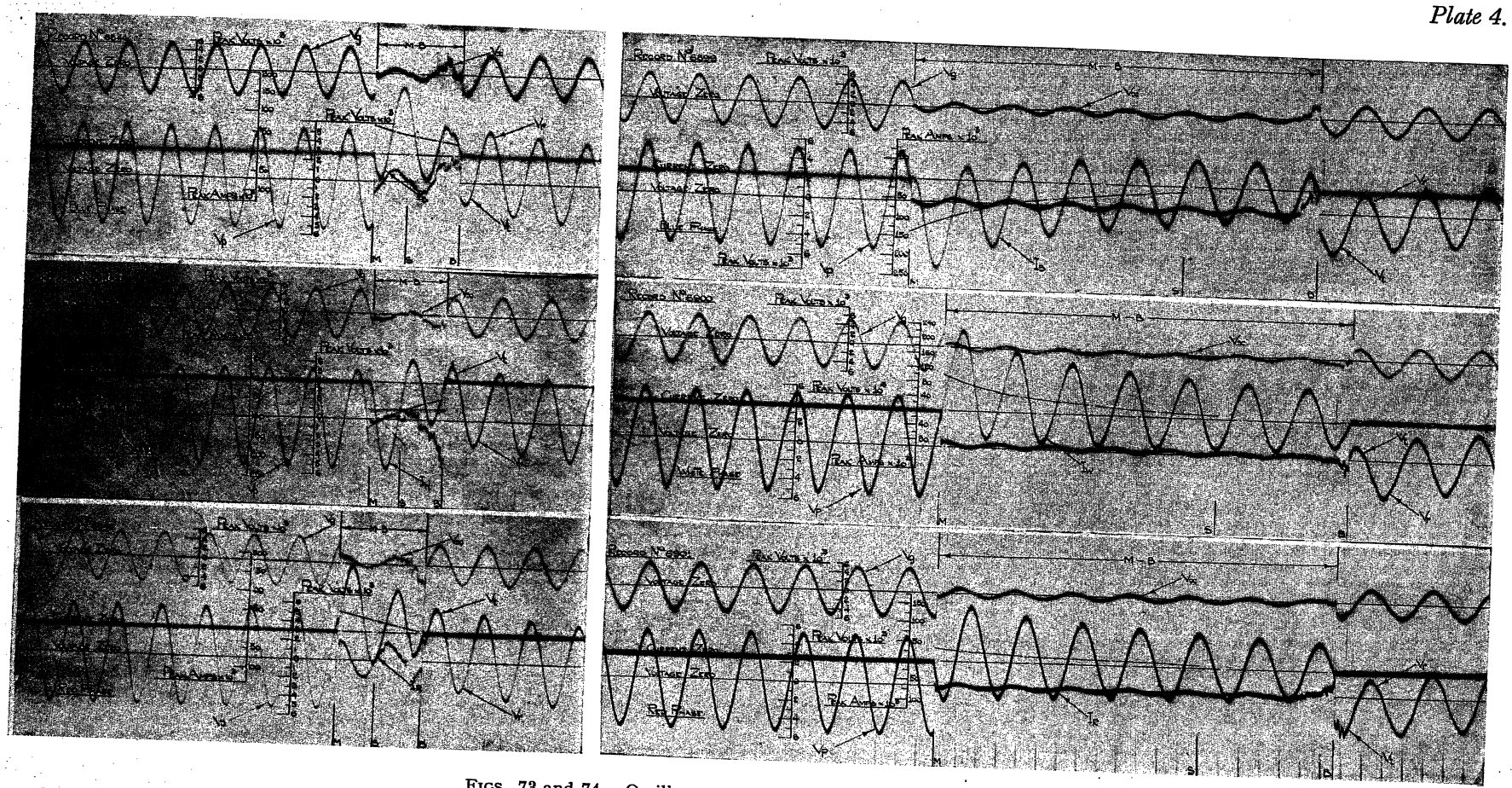
FIGS. 69 and 70.—Oscillograms of (1) Test No. 103A, and (2) 103B.

V_g.—Generator phase-voltage.
V_p.—Test circuit-breaker phase-voltage.
V_x.—Voltage across reactors and resistors.
V_t.—Transient restriking voltage.
V_r.—Recovery voltage.
I_B, I_W, I_R.—Short-circuit current.

M.—Short-circuit begins.
S.—Arcing contacts separate.
B.—Short-circuit cleared.
M–B.—Duration of short-circuit.
S–B.—Duration of arc.



FIGS. 71 and 72.—Oscillograms of (1) Test No. 244A, and (2) 244B.
(*See Plate 2 for key.*)



FIGS. 73 and 74.—Oscillograms of (1) Test No. 572B, and (2) 601.
(See Plate 2 for key.)

At the control room a pointer is driven by a similar timing device for a similar period, and indicates and records the reading of the remote meter. In this way meter readings and transformer-tapping positions recorded in the control room tally with those in the controlled stations.

In a regional control room operating on these lines the services provided by the 132 000-volt and 66 000-volt centrovisory control board are as follows:—

(1) Premeditated switching superimposed by hand on a system diagram.

(2) Automatic indication and comparison with (1) of the position of each circuit breaker.

(3) Alarm signal when a change of condition occurs, followed by automatic indication (2).

(4) Indication of the position of all transformer voltage-tappings.

(5) Alarm signal when any transformer tap-position is changed.

(6) Indication of kW input or output through the transformers and feeders.

(7) Indication as in (6) of the reactive kVA.

(8) Indication of voltage at selected positions on the system.

(9) Indication in kW of the total generator load at various stations.

(10) Transmission of stereotyped instruction-signals from the control room to various controlled stations.

(11) Telephone facilities from the control room to all controlled stations and extensions.

(12) Automatic lock-out on failure of pilot, or by key at will.

The control room is elliptical in shape, and approximately half of its periphery is occupied by the centrovisory control board. The remainder contains a system diagram, which forms a complete picture of the 132 000-volt, 66 000-volt, and 33 000-volt interconnected networks. The control engineer sits in the centre of the room at a desk that carries a condensed key-diagram of the whole system, and from this position he can maintain a correct record of all the connections on the large system-diagram.

Equipment with similar control dials is now being used for the remote control of outdoor transforming stations so distant from an available control room that the additional initial cost of the control is more than compensated by the saving in the multi-core cables that would be required for ordinary remote control. The control then includes, as an additional feature, the remote operation of circuit breakers and transformer taps, and thus advances a stage further in the direction of complete centrovisory control. One of the control boards is illustrated in Fig. 68, which shows that the several indications are given on two adjacent dials.

The foregoing indicates the progress made in the field of remote and automatic control, and the time is not far distant when regional control schemes will incorporate not only the direct operation of equipment by the control engineer, but also the further use of automatic control, which has already been tried out, for maintaining constant frequency, giving the possibility of a time-service and securing efficient interchange of load on the network. To this there may be added another function, over and above premeditated switching, namely, the giving of an indication, prior to actual switching, of what will be the effect of the switching. Thus the operator is relieved from mental strain, because of the rehearsal of each proposed performance beforehand.

The way in which the apparatus now coming into actual service extends, so to speak, both range of human vision and length of human arms is one of the important factors making for the success of any national or other widespread scheme.

The author takes this opportunity of acknowledging co-operation from his co-director, Mr. Frank Coates, and his staff, over many years in the design of the Reyrolle products, and from his colleagues, Mr. L. E. Mold and Mr. B. H. Leeson, in furthering the progress of the principles involved. He would also thank Mr. B. H. Leeson and Mr. T. Carter for the large amount of assistance he has received from them in the preparation of this paper as a whole, and other members of his staff, including Mr. W. A. A. Burgess, Mr. A. Allan, Mr. J. A. Harle, Mr. R. H. Brierly, Mr. D. E. Lambert, Mr. H. Leben, Mr. H. Rutherford, and Mr. A. Peel, for help with technical details and drawings.

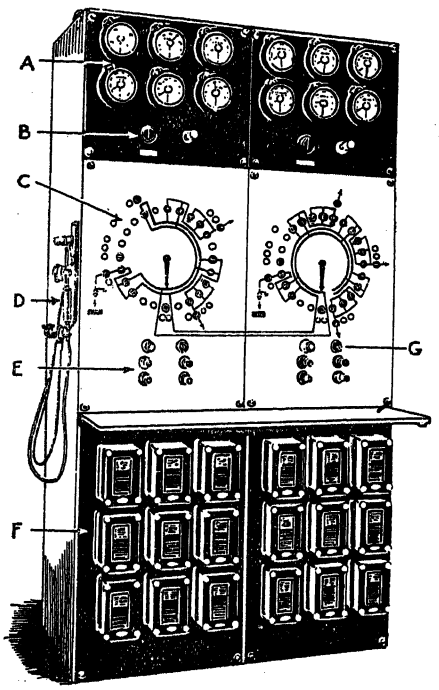


FIG. 68.

A.—Receiver instruments.
B.—General-alarm and stop-alarm pushes.
C.—Premeditated and position diagram.
D.—Telephone and plug.
E.—Control pushes.
F.—Operating relays.
G.—Lock-out key-switch.

REFERENCES TO EARLIER PAPERS.

(See footnote on page 286.)

H. W. CLOTHIER: "Construction of High-Tension Central-Station Switchgears, and Comparison of British and Foreign Methods," *Journal I.E.E.*, 1902, vol. 31, p. 1247.

H. W. CLOTHIER: "Switchgear and the Isolation of Faults on Power-Supply Systems," *Electrical Engineer* (London), 1910, vol. 46, p. 706. This paper dealt with metal-clad switchgear and Merz-Price protection (2-core and 3-core pilot, and core-balance leakage).

——"The Design of Electrical Plant, Control Gear, and Connections, for Protection against Shock, Fire, and Faults," *Journal I.E.E.*, 1925, vol. 63, p. 425.

APPENDIX I.

STANDARD CONDITIONS FOR SHORT-CIRCUIT TESTS OF CIRCUIT BREAKERS.

The predominant factors determining the severity or stress to which a circuit breaker is subjected, when undergoing short-circuit tests to establish its making-and-breaking-capacity performance, are as follows:—

(*a*) The rated voltage of the test circuit.
(*b*) The recovery voltage of the test circuit.
(*c*) The restriking voltage of the test circuit.
(*d*) The "making" current in the test circuit.
(*e*) The "breaking" current in the test circuit.
(*f*) The frequency in the test circuit.
(*g*) The power factor of the test circuit.
(*h*) The earthing of the test circuit.
(*i*) The type of short-circuit applied.
(*j*) The testing equipment used.
(*k*) The operating duty performed.

To ensure that a circuit breaker shall perform its rated "making" capacity and "breaking" capacity satisfactorily in service, it is necessary that the conditions under which the rating is assigned by short-circuit performance tests shall conform as closely as possible to the conditions of severity existing in service. The ideal practice would be for the test conditions to be adjusted to imitate exactly the conditions under which each individual circuit breaker is to be used. These conditions differ widely, however, and in addition to being difficult to calculate within any close limits of accuracy, they vary from time to time owing to the varying amount of plant and load connected to the network, and, further, they change as the plant and network extend. The practice actually adopted, therefore, is to standardize conditions of severity for performance tests in conformity with the average conditions encountered in service.

If a circuit breaker rated on the basis of a test performance obtained in this way is used under more severe conditions in service, its behaviour must be expected to differ also. Such differences between standard conditions and service conditions should be considered when selecting a standard circuit-breaker rating, and if the divergence is considerable, or likely to increase as the network extends, it may be necessary to select the next larger standard rating. Conversely, if the service conditions are easier than the test conditions, it may be permissible to select the next smaller rating.

In addition to standardizing conditions of severity for testing, it is of equal importance to standardize the method of interpreting the oscillograms obtained from short-circuit tests in terms of actual performance figures. Although B.S.S. No. 116–1929 goes a long way towards establishing the desired standard conditions and methods of interpreting oscillograms, it does not cover the requirements completely, and Clause 72(iii), which allows a test performance to be measured in terms of "kVA broken," requires modification in order to line up with the remainder of the Specification, which rates a circuit breaker on the value of the currents it will make and break at the rated voltage.

In the author's opinion, recovery voltage should be treated as a condition of severity in the standard test circuit, in the same way as the standard power factor.

The proposals set out on pages 319 and 320 are intended to assist in establishing an international method of proving the ratings of circuit breakers by standardized short-circuit performance tests; they are based upon average conditions of severity met with in service, as well as upon the experience gained with the aid of a British test plant,* and the behaviour of circuit breakers in service, judged over a period of 25 years.

The proposals standardize testing conditions and methods to be used for interpreting oscillograms, and specify what is virtually a standard test-circuit. Such of them as are applicable may also be used for tests of other devices, including cut-outs, switch-fuses, reactors, and transformers.

In practical application it has been found that the effects of deviations from the proposed standard conditions of severity usually average out satisfactorily, and two examples will illustrate this. The first is that a small circuit breaker rated at 100 000 kVA, and situated at the end of a long feeder with a large amount of generating plant feeding into it, is subjected to a recovery voltage of nearly 100 per cent, whereas the proposed standard recovery voltage is only 80 per cent; but this more onerous condition is compensated by the easement introduced by the improvement in the power-factor condition as compared with the standard of 0·1 lagging. As a second example, a large circuit breaker of, say, 1 000 000-kVA rating, situated in a generating station, will be subjected to as low a power factor as the standard 0·1 lagging; but the recovery voltage is likely to be less than the proposed standard 80 per cent. This means that the service conditions for this circuit breaker are likely to be easier than the test conditions; but this difference on the safe side is desirable in view of the importance of this circuit breaker on the network. In a minority of cases, the conditions, as already indicated, may be such that a larger standard circuit-breaker rating must be selected, or a smaller rating may be selected.

To sum up: The proposals for standardized performance tests are based upon what the author believes to be a fair representation of average conditions of severity met with in service, namely, those under which a circuit breaker would be required to operate on a short-circuit near to generating plant.

With a 10 000-kVA generator having 10 per cent reactance, a circuit breaker would have to break approxi-

* H. W. CLOTHIER: "The Hebburn Short-Circuit Testing Plant," *Electrical Review*, 1930, vol. 106, p. 996.

PROPOSALS FOR STANDARDIZED PERFORMANCE TESTS.

Item	Specification	Interpretation
(i) Circuit breaker under test	(1) A representative product erected under its service conditions (2) Below 66 000 volts, test 3-phase and 2-phase circuit breakers as complete units on a 3-phase or 2-phase test circuit respectively (3) At and above 66 000 volts, circuit breakers may be tested as single-phase units	The conditions specified imitate general practice in respect of circuit-breaker construction and permit the reproduction of the recovery voltages experienced in service at these rated voltages
(ii) Rated voltage	The standard voltage at which the circuit breaker is rated (B.S.S. No. 116–1929, Clause 47, Table I)	(*a*) The actual voltage of the test circuit may exceed the rated voltage for convenience or in order to obtain the specified recovery voltage (*b*) The voltage used to calculate performance shall be the rated voltage
(iii) Recovery voltage	80 per cent of the rated voltage, at the instant of final current-break	The recovery voltage shall be determined from the oscillograph record by taking the R.M.S. value of its normal-frequency alternating-current component extrapolated back to the point at which current is broken in the last phase to break. The specified value of 80 per cent is a minimum
(iv) Restriking voltage	Not specified numerically	The restriking voltage exists as a transient at the instant of arc extinction, and can only be measured by a cathode-ray oscillograph. These test-proposals do not include numerical values of the restriking voltage, but they implicitly control its order of magnitude and other characteristics by the necessity for including in the test circuit definite values of inductance, capacitance, and resistance, to produce the specified standard conditions
(v) Making current	Peak value of the current in the first major half-cycle after the arcing-contacts make circuit [B.S.S. No. 116–1929, Clause 72(i)]	See B.S.S. No. 116–1929, Fig. 2, in which the peak making-current includes the direct-current component
(vi) Breaking current	R.M.S. value of the current at the instant of separation of the arcing contacts [B.S.S. No. 116–1929, Clause 72(ii)]	See B.S.S. No. 116–1929, Figs. 1 and 2, in which the R.M.S. breaking-current includes the direct-current component
(vii) Frequency	50 cycles per second [B.S.S. No. 116–1929, Clause 44(2)]	
(viii) Power factor	0·1 lagging [B.S.S. No. 116–1929, Clause 44(3)(i)], measured at the instant of separation of the arcing contacts	(*a*) The power factor of each phase of the test circuit shall be the cosine of an angle ϕ determined from the oscillograph records of that phase after superimposing a continuation of the open-circuit voltage-wave on the short-circuit current-wave far enough to include the point at which contact separation occurs. The measurement shall be made as follows: (1) For symmetrical current-waves, ϕ shall be the angular distance between the initial zero of the half-cycle of the current wave in which contact-separation occurs and the superimposed-voltage-wave zero immediately preceding that current-wave zero

[*continued on page 320.*]

PROPOSALS FOR STANDARDIZED PERFORMANCE TESTS—*Continued.*

Item	Specification	Interpretation
(viii) Power factor (*cont.*)	0·1 lagging [B.S.S. No. 116–1929, Clause 44(3)(i)], measured at the instant of separation of the arcing-contacts	(2) For asymmetrical current-waves, ϕ shall be the angular distance between the initial zero of the alternating-current component of the half-cycle of the current wave in which contact-separation occurs and the superimposed-voltage-wave zero immediately preceding that current-wave zero (Note.—For convenience of measurement, the zero of the alternating-current component of the current wave may be projected vertically to the zero line of the superimposed voltage-wave.) (*b*) The power factor of a polyphase test-circuit shall be the cosine of the average of the angular distances ϕ of all the phases (*c*) For calculating the power factor before tests are made, the formula $\phi = \text{arc tan } (X/R)$ may be used, where X and R are the short-circuit values respectively of the reactance and the resistance of the test circuit
(ix) Earthing	(1) Below 66 000 volts, insulate the neutral point on the supply side of the test circuit (2) At and above 66 000 volts, solidly earth the neutral point on the supply side of the test circuit	The conditions specified imitate British practice, and (1) covers also earthing through a comparatively high resistance
(x) Short-circuit	Connect solidly to earth each pole on one side of the complete circuit breaker or of the single-phase unit under test	(*a*) The test circuit shall be so adjusted as to produce the specified standard conditions of severity, and the short-circuit current obtained from the testing equipment shall be regulated to the required value, by means of a combination of resistance and reactance in series, not in parallel, with each other, and/or by varying the field excitation of generating plant (*b*) Resistors, reactors, or condensers, except those authorized for measuring purposes, shall not be used in parallel with the circuit breaker
(xi) Testing equipment	(1) Below 3 300 volts, connect the circuit breaker to transforming plant (2) From 3 300 volts to 22 000 volts, connect the circuit breaker direct to generating plant (3) Above 22 000 volts, connect the circuit breaker to transforming plant	(*a*) The conditions specified imitate those usually applying in service at these voltages (*b*) The records of current, voltage, and power factor, shall be made by means of either electromagnetic or electrostatic oscillograph elements (*c*) The apparatus for measuring current shall consist of either shunts or current transformers inserted in the test-circuit, and the apparatus used for measuring voltage shall consist of voltage transformers, series resistors, or capacitative voltage-dividers (*d*) The connections between the circuit breaker under test and the source of the short-circuit power shall be of the shortest possible length
(xii) Operating duty	(1) Making capacity: M–2 : M–2 (B.S.S. No. 116–1929, Clauses 39 and 42) (2) Breaking capacity: B–2–MB–2 (B.S.S. No. 116–1929, Clauses 41 and 43)	"M" signifies *make circuit* "B" signifies *break circuit* "2" signifies *an interval of 2 minutes* "–" signifies *continuity* within a test cycle ":" signifies *a division* between test cycles
(xiii) Test certificate	A complete and precise record of the performance test, including the condition of the circuit breaker before the test, its behaviour during the test, and its condition after the test	The test certificate shall specifically state any departures from the standard conditions and methods of interpretation, and shall indicate whether such departures increase or diminish the severity as compared with the standard

mately 100 000 kVA on a short-circuit with normal conditions of tripping. On rare occasions, however, it might open on the first half-cycle of the short-circuit transient, and would then have to deal with a possible maximum of the order of 133 000 kVA.* A correct interpretation of the performance tests under standard conditions will indicate what standard rating a circuit breaker must have to ensure its suitability for this service.

APPENDIX II.

Some Short-Circuit Tests of Circuit Breakers.

The breaking-capacity ratings assigned to British circuit breakers are based on standard breaking-capacity currents at given rated voltages in accordance with B.S.S. No. 116–1929. A size to which such a rating is assigned has also, for convenience, a standard kVA rating, obtained by multiplying the standard current-breaking-capacity rating by the rated voltage and by the appropriate phase factor. For instance, a 3-phase circuit breaker of a size† and strength suitable for a current-breaking capacity of 5 200 amperes at 11 000 volts, or 8 800 amperes at 6 600 volts, is also known as a 100 000-kVA circuit breaker (Table IV, B.S.S. No. 116–1929).

Short-circuit tests in Great Britain and abroad show that British circuit breakers perform consistently at and above the rated breaking-capacity currents associated with the standard kVA allocated to them; and a few examples of a large number of 3-phase tests carried out with the aid of a British test plant are summarized in tabular form on pages 322–327. Typical oscillograms, representative of many repeat tests, are shown in Figs. 69 to 74 (Plates 2, 3, and 4), and relate to Tests Nos. 103A, 103B, 244A, 244B, 572,B and 601.

The tests were carried out under the conditions of the standard circuit outlined in Appendix I, and the records were made with oscillograph apparatus of the standard electromagnetic type.

In the majority of the tests the recovery voltage was higher than the author's proposed standard condition of severity of 80 per cent; and in respect of operating duty some tests were more severe than the standard, and some less, as indicated in the operating-duty column. The values of the restriking voltage were not tabulated. The normal frequency of the test supply was 40 cycles per second. The performance of the circuit breakers was in all cases such as to show their entire suitability for their standard ratings.

* It has been claimed on the Continent that in the case of complete asymmetry of current in an inductive circuit the restriking transient voltage is of zero value at the same time as the current. In such a hypothetical case the break is easy. On these premises it is proposed that the direct-current component should be disregarded in calculating the performance kVA. On the other hand, it must not be overlooked that amongst the factors apt to damage circuit breakers in action are the mechanical stress produced by electromagnetic forces and the rate of generation of the gas bubble, which tend to distort the constructional mechanism; and these, together with burning of the arcing contacts, depend upon the magnitude of the resultant of the alternating-current and direct-current components, no matter what method of calculation is arbitrarily agreed upon. Hence the British practice, like the American, has been, and still is, to include the direct-current component. This is important in respect of the maximum of 133 000 kVA referred to here, because the excess over 100 000 kVA is due to the direct-current component; and if it is true that this may be disregarded (which has yet to be proved conclusively by comparative tests on the basis of the stress produced in the enclosure and on the mechanism), the circuit breaker selected need not have a larger rating to deal with the contingency.

† L. C. Grant: *Journal I.E.E.*, 1930, vol. 68, p. 1101, Table 9 and Fig. 25.

APPENDIX III.

Reactance versus Impedance Measurements for Distance Relays.

When applying protection by means of time/distance relays of the time class to overhead transmission lines, it is of paramount importance to decide what quantity the relays should measure in order to provide time-discrimination proportional to the distance of the fault from the relay. Although, in general, correct discrimination may be obtained for heavy earth or phase faults on overhead lines, and for cables, by the use of relays operating on an impedance measurement, nevertheless, on networks of the type of the 132 000-volt British grid, where it is as important to clear small earth-faults as the heavier ones, any time/distance relay protection must be designed fundamentally to meet this requirement. There are three quantities associated with an earth-fault loop, namely, its resistance, its impedance, and its reactance, any one of which might on a first consideration be thought to be proportional to the length of the loop, and therefore suitable as a basis for the required measurement. Further consideration and investigation, however, show that the resistance of an earth-fault loop may vary in many ways, owing to the introduction into the circuit of external resistance, such as the contact resistance of earth plates, the variable resistance of the earth, the contact resistance between the conductor and earth in a broken line, and the resistance of the arcing fault itself, of which more is said below. It has also been shown by tests* carried out by the British Electrical Research Association that the reactance component of the earth-fault loop is reasonably constant.

It will be proved in what follows that the arc resistance is variable, and by no means always negligible in amount; and since it is included in the total resistance of the earth-fault loop, the impedance of the loop contains a variable quantity that may make its value uncertain. The reactance of the loop, however, is not dependent upon the resistance; and therefore distance relays of the reactance type are not affected, but the operation and discrimination of impedance-type relays are directly affected. The seriousness of the effect of arcing faults on the operation of impedance-type relays depends upon the relation between the values of the resistance of the earth-return path and of the arcing fault and the reactance of the earth-fault loop. Since the latter quantity is usually small (approximately 1 ohm per mile of earth-fault loop on the 132 000-volt British grid), even a small resistance in the arcing fault has a considerable effect upon the apparent impedance of the earth-fault loop.

To determine the amount by which the resistance of an arc may affect the correct discrimination of distance relays, tests of power arcs in air, such as occur on overhead transmission lines, were carried out with the aid of a British test-plant. These tests, which are described below, indicate that the resistance of such arcs is a variable quantity, depending upon the length of the arc, the wind velocity, the time during which the arc persists, and the way by which the arc is drawn out. Of these factors, the duration of the arc is of particular

* *Journal I.E.E.*, 1930, vol. 68, p. 867.

TESTS OF 100 000-kVA THREE-PHASE CIRCUIT BREAKERS WITH STANDARD RATINGS

(*a*) 11 000 volts, 5 200 amperes.
(*b*) 6 600 volts, 8 800 amperes.
(*c*) 3 300 volts, 17 600 amperes.

(*a*) *Tests at* 11 000 *Volts* (*Standard rating* 11 000 *volts*, 5 200 *amperes*) *with neutral earthed through* 6·3 *ohms.*

Test number	Part of test	Operating duty	Test voltage per phase	Peak amperes per phase in first half-cycle	Breaking current (R.M.S. amperes) per phase	Recovery voltage per phase	Arcing period, half-cycles per phase	Power factor (lagging) of test circuit	Percentage ratio of breaking current to rated breaking current	Remarks
98	A	B	6 350	17 800	7 240	6 200	2·25	0·1	130	Very quiet. Slight puffs of smoke from vents during each operation. Arcing contacts moderately burnt, and renewed for next test, No. 99
				16 800	6 850	5 610	3·0			
		2		9 870	6 310	5 850	3·0			
	B	MB	6 350	17 600	7 820	6 000	2·5	0·1	142	
				9 400	6 100	6 350	3·0			
		2		17 720	8 280	6 230	2·0			
	C	MB	6 350	14 760	7 100	6 060	2·75	0·1	135	
				17 600	7 625	6 260	2·25			
		2		12 490	6 340	6 260	3·0			
	D	MB	6 350	15 160	6 860	6 200	2·5	0·1	122	
				12 400	6 400	5 560	3·0			
				11 080	5 830	5 960	1·75			
99	A	B	6 350	10 000	6 230	5 350	2·25	0·1	130	Very quiet. Slight emission of oil and smoke from vents during each operation. Arcing contacts slightly burnt, but not sufficiently to require renewal before next test, No. 100
				16 400	7 200	5 620	2·0			
		2		17 200	7 000	4 900	2·75			
	B	MB	6 350	10 000	6 260	5 350	2·75	0·1	130	
				16 400	7 200	5 720	3·5			
		2		16 000	6 800	5 140	3·5			
	C	MB	6 350	11 200	6 520	5 300	3·25	0·1	130	
				17 000	7 000	5 675	3·0			
		2		15 000	6 670	5 150	3·25			
	D	MB	6 350	12 800	6 520	5 300	3·0	0·1	127	
				16 000	7 000	5 675	3·25			
				12 400	6 340	5 190	3·75			

100	A	B 2	6 350	16 000 / 9 200 / 16 400	6 400 / 6 360 / 7 140	5 300 / 5 625 / 5 100	3·0 / 2·75 / 3·25	0·1	133	Very quiet during A and B; but 14 tests had been made (including 4 not recorded here, as well as Nos. 98 A–D, 99 A–D, and 100 A–B) without overhaul of the circuit breaker, except renewal of oil and contacts when required; and, probably because the usual carbon and metal deposit was not removed, but had accumulated abnormally on the internal parts, jamming of the guide-rods in their bearings, which is not possible under normal conditions, took place during C, just after the contacts had separated, and continuous arcing ensued. Tank badly damaged and top-plate slightly distorted without damage to hoods. Slight flame and considerable loss of oil. New tank fitted, and top-plate straightened by machining prior to next test, No. 101
	B	MB 2	6 350	17 200 / 16 000 / 10 400	7 850 / 7 400 / 6 400	5 400 / 5 825 / 5 200	2·75 / 3·0 / 3·75	0·1	138	
	C	MB	6 350	14 000 / 17 600 / 12 000	7 050 / 7 050 / 6 630	— / — / —	— / — / —	0·1	133	
101	A	B 2	6 350	15 600 / 11 600 / 18 000	6 820 / 6 280 / 6 760	5 625 / 5 830 / 5 500	1·5 / 2·5 / 1·75	0·1	127	
	B	MB 5	6 350	13 200 / 14 400 / 18 600	6 560 / 6 790 / 7 000	5 180 / 5 680 / 5 625	3·5 / 3·5 / 3·25	0·1	130	Very quiet. No oil and only very slight puffs of smoke from vents. Contacts moderately burnt, and renewed for next test, No. 102
	C	B 2	6 350	17 800 / 14 000 / 13 000	6 800 / 6 420 / 6 150	5 560 / 5 625 / 5 625	3·0 / 2·25 / 4·0	0·1	124	
	D	MB	6 350	13 200 / 17 600 / 13 800	7 000 / 7 060 / 6 860	5 625 / 5 840 / 5 780	3·5 / 3·5 / 4·0	0·1	134	
102	A	B 2	6 350	10 800 / 17 600 / 16 400	6 430 / 8 000 / 7 270	5 740 / 5 730 / 5 780	2·5 / 2·5 / 2·75	0·1	145	Very easy. Very small amounts of oil with puffs of smoke from vents. Contacts slightly burnt, and only needed cleaning up before next test, No. 103
	B	MB	6 350	17 600 / 9 600 / 17 600	7 630 / 6 250 / 8 000	5 790 / 5 680 / 5 730	3·25 / 2·25 / 2·75	0·1	140	
103	A	B 2	6 350	21 790 / 18 410 / 14 550	8 950 / 8 150 / 7 900	5 940 / 6 120 / 5 860	2·5 / 2·0 / 2·25	0·1	160	Very easy. Slight emission of oil and smoke through vents. Circuit breaker in perfect condition with the exception of slight burning on the arcing contacts
	B	MB	6 350	13 780 / 21 600 / 19 500	7 920 / 9 900 / 8 950	6 050 / 6 040 / 6 060	2·0 / 2·5 / 2·5	0·1	173	

TESTS (*continued*) OF 100 000-kVA THREE-PHASE CIRCUIT BREAKERS WITH STANDARD RATINGS

(*a*) 11 000 volts, 5 200 amperes.

(*b*) 6 600 volts, 8 800 amperes.

(*c*) 3 300 volts, 17 600 amperes.

A series of tests was carried out on another circuit breaker of the same type, to prove its suitability for a 15 000-volt system. During this series, of which the following examples are typical, the test voltage was increased to 16 000 volts for the purpose of maintaining the specified 80 per cent recovery voltage. The neutral was earthed through 12·7 ohms.

Test number	Part of test	Operating duty	Test voltage per phase	Peak amperes per phase in first half-cycle	Breaking current (R.M.S. amperes) per phase	Recovery voltage per phase	Arcing period, half-cycles per phase	Power factor (lagging) of test circuit	Percentage ratio of breaking current to rated breaking current	Remarks
188	A	B	9 240	16 400	6 420	7 600	3·0	0·1	115	Easy. Hiss of escaping gas and slight oil discharge from vents. Contacts, which had been used on previous tests, only slightly more burnt, and retained for next test, No. 189
		2		10 400	5 290	7 780	3·0			
				17 200	6 280	7 600	2·5			
	B	MB	9 240	18 000	6 960	7 780	3·0	0·1	120	
				15 200	6 240	7 700	2·0			
				10 000	5 660	7 600	3·5			
189	—	B	9 240	17 800	6 480	7 760	3·25	0·1	117	Quiet. A little oil and a puff of smoke through vents. Arcing contacts burnt, and renewed for next test, No. 190
				15 200	5 900	7 760	3·5			
				10 000	5 880	7 760	3·5			
190	A	B	9 240	16 600	6 890	7 780	2·5	0·1	125	Easy. Slight oil-throwing and puff of smoke from vents. Contacts slightly burnt, but used during next test, No. 191
		2		11 600	5 880	7 780	2·0			
				18 400	7 070	7 780	1·75			
	B	MB	9 240	19 600	7 030	7 430	2·25	0·1	130	
				17 400	6 690	7 760	2·0			
				10 800	5 900	7 430	2·5			
(*b*) *Tests at* 6 350 *Volts* (*Standard rating* 6 600 *volts*, 8 800 *amperes*) *with neutral insulated.*										
105	A	B	3 660	19 000	9 700	3 270	0·75	0·1	115	With the exception of new contacts, circuit breaker in same condition as after test No. 103. Operation good. Slight emission of oil through vents. Arcing contacts moderately burnt. Main contacts slightly pitted, but suitable for service conditions. Contacts cleaned before next test, No. 106
		2		26 300	10 800	3 780	1·0			
				20 500	10 000	3 230	1·0			
	B	MB	3 660	30 000	13 100	3 660	1·0	0·1	130	
				20 850	10 100	3 790	1·25			
				24 500	11 600	3 530	1·5			

106	A	B	3 660	35 500	14 500	3 490	1·75	0·1	155	Quiet. Small emission of oil from vents. Slight extra burning on all contacts, and tank lining distorted, but circuit breaker good for service again without adjustment
				26 000	13 300	3 420	1·5			
		2		29 000	13 700	3 320	2·25			
	B	MB	3 660	37 000	16 850	3 490	1·75	0·1	170	
				25 000	13 530	3 530	1·5			
				32 000	14 500	2 950	1·75			

Tests at 6 350 volts on another circuit breaker of the same type. Test-circuit conditions the same as for Tests Nos. 105 and 106. Circuit-breaker contacts slightly burnt as a result of previous tests.

165	A	B	3 660	27 500	13 450	3 080	1·0	0·1	160	Easy. Slight spray of oil and puff of smoke. Contacts moderately burnt, and renewed before next test, No. 166
				29 000	14 100	3 670	1·5			
		2		36 000	14 540	3 280	1·25			
	B	MB	3 660	34 000	14 540	3 080	2·25	0·1	160	
				35 000	15 100	3 710	2·5			
				19 000	13 600	3 340	2·5			
166	A	B	3 660	37 700	15 510	3 350	0·5	0·1	165	Quiet. Slight emission of oil from vents and tank flanges. Puffs of smoke. Visible jump during B. Contacts moderately burnt, and renewed before next test, No. 167
				26 950	14 050	3 320	0·75			
		2		32 550	14 450	3 450	0·75			
	B	MB	3 660	35 160	15 700	3 490	1·0	0·1	175	
				24 400	14 600	3 390	1·0			
				37 970	16 900	3 540	0·75			
167	A	B	3 660	37 000	18 000	2 860	1·0	0·1	215	Not so quiet. Slight emission of oil through tank flanges. Arcing contacts rather badly burnt, but circuit breaker fit for service without adjustment
				52 000	20 700	3 140	1·25			
		2		41 000	18 900	3 290	1·75			
	B	MB	3 660	31 000	17 800	2 970	1·0	0·1	240	
				50 000	20 500	3 560	0·75			
				54 000	20 820	3 290	1·5			

(c) Tests at 4 400 *Volts (Standard rating* 3 300 *volts,* 17 600 *amperes) with neutral insulated.*

109	A	B	2 540	51 000	21 000	2 160	1·5	0·1	125	Easy. Slight emission of oil from vents. Slight burning on all contacts
				51 000	21 800	2 140	1·75			
		2		64 000	22 400	2 160	1·25			
	B	MB	2 540	66 000	23 200	2 160	1·0	0·1	125	
				45 000	21 400	2 200	1·25			
				56 000	22 400	2 210	1·25			

TESTS OF A 100 000-kVA THREE-PHASE CIRCUIT BREAKER UNDER FREAK CONDITIONS.

(Tests Nos. 225 to 228.)

A series of four tests was carried out on the circuit breaker used in tests Nos. 165 to 167 recorded above, but with the tank strength reduced by the omission of one tank-stud, and with the total length of break limited to $\frac{3}{4}$ in. (two breaks of $\frac{3}{8}$ in. each). The object of the tests was to discover the effect on the behaviour of the circuit breaker of a hold-up of the plunger-bar travel, owing, for example, to a mechanical defect. The neutral point was insulated during this series. Tests were made with 3 500 amperes at 11 000 volts (No. 225), 6 500 amperes at 6 350 volts (No. 226), and 9 500 amperes at 9 000 volts (No. 227). During these three tests, the maximum arc-duration was 4 half-cycles, and the circuit breaker operated quietly, emitting a slight amount of oil and smoke from the vents. The contacts were not changed, and no adjustments were made to the circuit breaker before the next test, No. 228, which is recorded in detail below.

Test number	Part of test	Operating duty	Test voltage per phase	Peak amperes per phase in first half-cycle	Breaking current (R.M.S. amperes) per phase	Recovery voltage per phase	Arcing period, half-cycles per phase	Power factor (lagging) of test circuit	Percentage ratio of breaking current to rated breaking current	Remarks
228	—	B	6 350	31 200 18 400 32 800	12 300 10 900 13 470	5 530 5 750 5 730	Intermittent arcing for 12 half-cycles	0·1	230	Circuit breaker cleared short-circuit, but high pressure due to arcing period caused weakened tank-flange to bulge $\frac{5}{8}$ in. A tank-stud sheared off. Heavy discharge of oil through flange, and much smoke but no flame

TESTS OF 250 000-kVA CIRCUIT BREAKERS WITH STANDARD RATING 11 000 VOLTS, 13 000 AMPERES.

(a) Tests of a Hand-operated Circuit Breaker with neutral insulated.

255	A	B	6 350	37 760	16 450	5 150	1·0	0·1	133	Easy on A, heavier on B. Slight emission of oil through rope-guides. Arcing contacts burnt, but not renewed for next test, No. 256
				55 850	18 350	4 950	1·5			
		2		47 150	17 600	5 120	1·5			
	B	B	6 350	52 550	17 300	5 620	1·0	0·1	130	
				51 800	17 420	5 120	1·5			
				31 900	16 500	5 300	2·0			
256	A	B	6 350	61 300	19 900	4 910	1·0	0·1	150	Heavy on A, easier on B. Emission of oil and smoke from rope-guides and vents. Tank barriers deflected slightly, breaking wood lining. Arcing contacts only slightly burnt, and switch suitable for service again without adjustment. Tank lining repaired before next test, No. 257, but same contacts used
				55 300	19 900	4 890	1·25			
		2		39 850	19 200	4 830	1·25			
	B	B	6 350	62 300	19 560	4 990	0·50	0·1	150	
				55 300	20 000	5 050	0·75			
				41 100	19 300	4 990	1·0			

257	A	B	6 350	45 100	20 550	5 510	1·0	0·1	170	Quiet on A, heavier on B. Little oil thrown through rope-guides. Arcing contacts now rather badly burnt
				63 100	24 800	5 500	1·75			
				50 900	21 800	5 770	0·75			
		2								
	B	B	6 350	63 600	26 600	5 570	1·0	0·1	180	
				58 500	23 100	6 240	1·0			
				40 680	20 570	5 560	1·5			

(*b*) *Tests of a Solenoid-operated Circuit Breaker with neutral earthed through* 6·3 *ohms.*

244	A	B	6 350	51 200	20 950	5 590	1·25	0·1	145	Easy. Oil and smoke emitted from hood-flange and vents. Wood lining displaced and arcing contacts rather badly burnt, but circuit breaker fit for service again without adjustment
				43 350	18 550	5 750	1·0			
				36 880	18 250	5 520	1·25			
		2								
	B	MB	6 350	53 450	21 400	5 450	0·75	0·1	145	
				41 430	19 250	5 590	1·0			
				37 260	18 400	5 620	1·0			

TESTS OF A 1 000 000-kVA CIRCUIT BREAKER WITH STANDARD RATING 6 600 VOLTS, 88 000 AMPERES: NEUTRAL INSULATED.

The following tests were carried out to prove the suitability of this circuit breaker for a 6 000/6 300-volt system.

419	—	MB	3 450	257 100	145 500	4 100	1·5	0·1	140	Switch cleared very sharply. Slight emission of oil from tank flanges and vents. Main contacts clean, but arcing contacts rather heavily burnt
				170 000	101 500	Records	Records			
				215 000	127 000	spoilt	spoilt			
421	—	B	3 450	192 000	72 000	2 700	2·5	0·1	98	With new arcing contacts. Easy operation. Slight emission of oil from vents. Arcing contacts only slightly burnt
				242 000	100 000	2 800	2·0			
				181 000	85 000	2 700	2·5			
549	—	B	3 450	185 800	92 500	3 060	2·0	0·1	113	Arcing contacts in same condition as after previous tests. Operation very quiet. Slight emission of oil from vents. Arcing contacts now badly burnt, and renewed
				151 650	90 300	2 930	2·5			
				214 000	119 500	2 980	2·0			
572	B	B	3 640	163 500	91 250	2 910	2·5	0·1	110	With moderately-burnt contacts. Operation exceptionally quiet. Only slightly more burning. Little oil through vents
				225 000	116 000	2 910	2·0			
				166 000	84 000	3 060	2·0			

The following test was made primarily to prove the straight-through carrying-capacity of the circuit breaker.

601	—	Straight through, followed by break	3 580	229 000	60 500	2 100	4·2	0·1	—	Contacts as used on previous tests. Operation very quiet. Contacts only slightly burnt
				220 400	66 400	2 070	3·5			
				144 500	59 200	2 010	4·5			

importance, in view of the fact that the protective system itself is of the time class. Fig. 75 shows the diagram of connections, and is self-explanatory. The arc was started by means of thin copper wire bridging the two porcelain insulators spaced 6 ft. apart, and the voltage across it was measured by means of a voltage

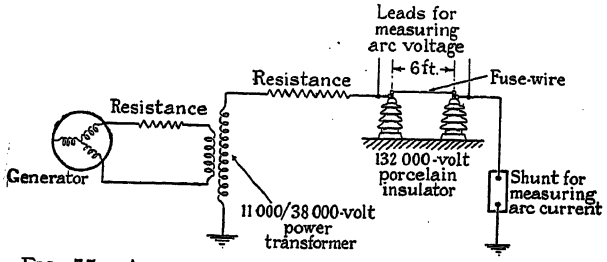


FIG. 75.—Arrangement of plant for tests of power-arcs.

transformer. Both current and voltage were recorded by an oscillograph.

The tests were carried out on a calm day, and there was therefore no undue spreading of the arc by wind, which would tend to increase its resistance. The results are shown in four curves in Fig. 76, which give the arc resistance with various currents after time-intervals of 0·22, 0·45, 0·67, and 0·90 second from the start of the arc. Broadly speaking, the arc resistance decreases as the arc-fault current increases, and increases with increasing length and with increasing time. As was to be expected, the behaviour of the arc was erratic, and it is difficult to forecast the probable variation of the resistance of an arcing fault in actual practice. Since the resistance values shown in Fig. 76 were determined on a calm day, they represent the minimum values likely to be experienced in service, and will suffice to illustrate how the desired discrimination is not necessarily given under all conditions by impedance-type relays.

One of the results of the 132 000-volt British grid will be that generating plant found to be unnecessary will be shut down during periods of off-peak load, and therefore a fundamental requirement of any time/distance type of protection must be to discriminate correctly under such off-peak-load conditions when an earth fault occurs at some distance from a generating station. A study of these conditions indicates that fault currents of the order of 500 amperes are likely to be experienced. On the basis of the curve in Fig. 76 for 0·67 sec., which is taken as being less than the operating time required by the relay at the far end of the feeder, this means that the arc resistance is of the order of 10 ohms. If, as is possible, the fault occurs on a 15-mile 132 000-volt line, which has of itself a total earth-fault-loop reactance of about 15 ohms, the effect is to give an impedance-type relay a falsely related time-delay. The arc resistance continues to increase, and after 0·90 sec. reaches a value of 16 ohms. The process is thus cumulative; and it must be remembered that the values given have to be increased by adding the total earth-plate resistance, which may be as much as 4 ohms. Thus, should the assumed fault occur, say, 12 miles along the 15-mile line, the impedance of the earth-fault loop, excluding the arc resistance, will be about 14 ohms (about 12 ohms reactance and about 3 ohms line resistance, plus about 4 ohms earth-plate resistance); but impedance relays, instead of adjusting their time-delay to this value, will falsely adjust it to an impedance of about 26 ohms (about 12 ohms reactance and about 3 ohms line resistance, plus about 16 ohms arc resistance, plus about 4 ohms earth-plate resistance). This is equivalent to the indication of a fault nearly 100 per cent too far away; and the shorter the line the greater will be the falsifying influence of the arc resistance.

Since the arc resistance diminishes with increasing fault-currents, it is under conditions causing very heavy fault-currents to flow that impedance-type relays give

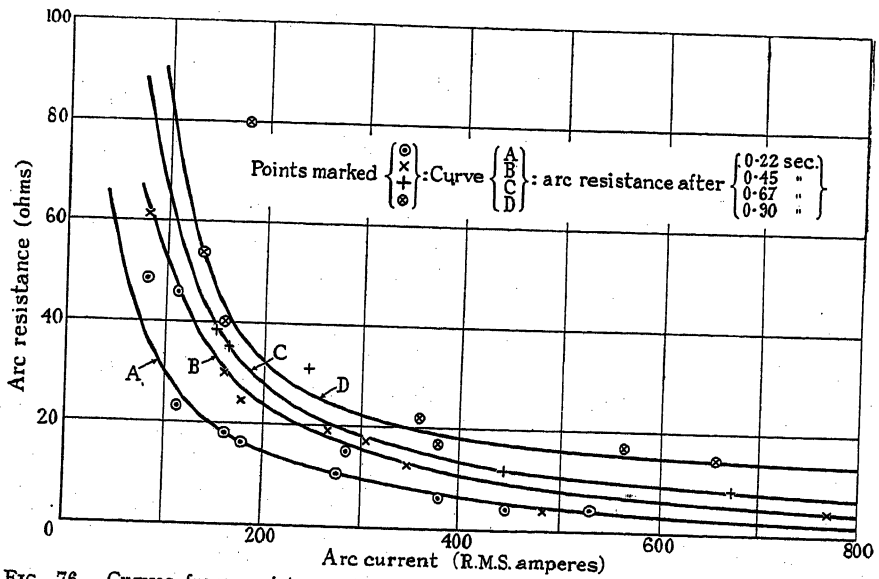


FIG. 76.—Curves from resistance tests of power arcs at 38 000 volts, i.e. 66 000-volt, 3-phase conditions.

their most correct discrimination. On the other hand, reactance-type relays discriminate correctly, irrespective of the magnitude of the fault current, or of the value of the resistance introduced into the fault loop by earth-path or arc resistance.

APPENDIX IV.

The Safeguarding of Post-Office Pilots Associated with Power Networks.

(*i*) *Conditions to be Met.*—Post-Office pairs or channels of communication may be associated with high-voltage power-lines as pilot wires either for automatic power-line protective systems, or for remote control and indication of meter readings. Investigation shows that it is necessary to guard against the following two causes of possible danger to Post-Office pilot wires and the apparatus connected to them (see Fig. 58 on page 313):—

(1) Failure of the high-voltage insulation between the power line and the secondary wiring associated with the Post-Office pilots; for example, the current transformer.

(2) Momentary rise in potential to earth of the secondary wiring and apparatus connected to the pilot wires as a result of an earth fault on the high-voltage power system.

The first of these is very unlikely to occur in practice, but if it does it imposes very severe stress on the protective gear, control equipment, or other apparatus connected to the Post-Office pilot wires. The second state, however, exists every time an earth-fault occurs on the high-voltage power system; but, unlike the first, it imposes comparatively little severity on the apparatus connected to the Post-Office pilot wires. The rises in potential to earth that can occur are of the order of a few thousand volts, depending upon the value of the power fault-current and the impedance offered to it by the earth-return path. The various conditions under which such potential-rises can occur are not dealt with in detail here.

(*ii*) *Provision for Safety.*—The precautions for safety must in every case take into account the two causes of possible danger just described; but it may be convenient to consider them in relation to the two common conditions in practice of association between the equipment connected to a power network and that connected to Post-Office pilot wires: (*a*) the association may be all within a building or site constituting a generating or transforming station; or (*b*) the association may be within a building, such as an isolated control room, in which it only occurs because a connection to the power network enters for the usual purposes of electricity supply.

Fig. 58 shows diagrammatically the precautions proved to be adequate for ensuring the safety of protective or control apparatus utilizing Post-Office equipment associated under condition (*a*) with current transformers housed in the switchgear controlling a high-voltage line.

The primary safeguard was found in the use of an earthing device incorporated in the high-voltage switchgear and connected to the secondary wiring and the station earth-plate. The object of this is two-fold: First, it ensures that the power-line protective gear automatically isolates the high-voltage power line should the insulation of the current transformer fail, and, secondly, it reduces the voltage imposed on the secondary wiring, which might otherwise be the full voltage of the power line, to merely the voltage-drop across the spark-gap.

A second requisite safeguard was found to lie in the termination and separate earthing of the sheath of the Post-Office pilot wires at least 50 yards away from the earth plate associated with the high-voltage switchgear controlling the power line. The object of this is to prevent the lead sheath of the pilot wires from being subjected to undue voltage-rise when an earth-fault current is passing through the station earth-plate. In addition, the pilot wires themselves are protected quite independently by means of standard Post-Office over-voltage and heat-coil devices connected to the pilot earth.

Additional security has been obtained by adopting either the "physical-separation" method or the "separated-circuit" method of arranging the protective, control, or other apparatus, associated with the secondary wiring of the high-voltage power-line on the one side, and with the Post-Office pilots on the other. "Physical separation" is shown on the left-hand side of Fig. 58 and a "separated circuit" on the right-hand side. Either method provides additional security, and the choice between them is governed by consideration of which is the easier of the two to apply to the particular type of apparatus employed.

Under condition (*b*), the precautions necessary to prevent control-apparatus, situated, for example, in an isolated control room, from being subjected to earth voltage-rises caused by faults on the power-network have been found to be that the lighting or power-supply cables should have their lead sheaths and armourings separately earthed at least 50 yards from the control room, the supply being taken into the building through insulated cables, and that the sheath of the pilot wires should be terminated and earthed, and the pilot wires protected, in the same way as under condition (*a*).

(*iii*) *Pressure-Tests.*—It has been agreed by the parties concerned that the secondary wiring associated with the power line, and the secondary wiring associated with the Post-Office pilot wires, must be physically separated, and must be capable of withstanding the following tests:—

	Momentarily	For 2 minutes
For power lines above 33 000 volts	15 000 volts	5 000 volts
For power lines of 33 000 volts and under	3 750 volts	1 250 volts

Insulated enclosures must withstand 3 750 volts to earth momentarily, and 1 250 volts for 2 minutes; and all apparatus must withstand 2 000 volts for 1 minute between live metal parts and their enclosure.

(*iv*) *Safety Afforded.*—Fig. 58 shows that, before the Post-Office protective device is called upon to function and to protect the Post-Office pilots in the ordinary way,

three stages of insulation failure must take place, namely:—

(1) A breakdown of the insulation of the instrument transformer.
(2) A failure of apparatus within the earthed enclosure.
(3) A failure of apparatus within the insulated enclosure.

Safety against breakdown due to rises in voltage to earth is afforded by using apparatus designed to withstand the pressure tests specified above.

(*v*) *Power Tests.*—A number of tests to establish the efficacy of the safety precautions were carried out with the aid of a British test-plant, the apparatus and connections being so arranged as to represent actual service conditions. The apparatus complied with the pressure tests specified above, and earthing devices designed especially for the purpose were used.

A series of tests was made to determine whether a momentary voltage of any appreciable magnitude existed between the contacts marked A and the earthed case marked B in the "separated circuit" shown in Fig. 58. A neon lamp and a photographic plate were used as a means of detecting the existence of any such voltage. The insulation of the current transformer was bared in one place, so that when 19 000 volts to earth was applied to the line (corresponding to the voltage of a 33 000-volt network) this voltage was applied practically instantaneously to the secondary wiring of the current transformer. With currents of the order of 1 750 amperes (corresponding to a 3-phase power of 100 000 kVA at 33 000 volts) no voltage was indicated on the photographic plate, and so it was proved that the relay was not subject to any over-voltage stress. The spark-gaps easily carried the fault current, thus isolating the high-voltage power line.

In general, the tests carried out indicated that, subject to the taking of adequate precautions, Post-Office pairs or channels of communication can be used with complete safety in association with high-voltage power lines.

Discussion before The Institution, 25th February, 1932.

Mr. W. A. Coates: I should like to refer to a method of isolation which is not mentioned in the paper. It was, I think, patented by the A.E.G. company in 1912, and it differs from the author's arrangement shown in Fig. 15 in that whereas the latter has separately-operated isolating switches, this German design (see Fig. A) merely has plug contacts in an oil vessel. The practical development of this arrangement is to-day being applied in one of London's big power stations. In this case the main busbar is in U formation and runs right round the building, the auxiliary busbar being placed in the centre. Above are oil chambers carrying the isolating device and the circuit breaker with which it is linked. This system is designed for 66 000 volts, but, unlike the arrangements which we have seen hitherto, the busbars are not oil-filled for purposes of insulation; they are practically condenser bushings. The only oil used is employed in the isolating chamber, in all the junction boxes, and in the switch itself; everywhere else the conductors are wrapped with solid dielectric, applied as on a condenser bushing. The 66 000-volt circuit breaker employed weighs about 20 tons, and an oil vessel covers the junction between the plug-contact insulator and the switch proper. The control board is an excellent example of the clear system indication suggested in the paper; the busbars and the various pieces of apparatus are all indicated in clear glass, behind which there are three different coloured lights which are used to indicate that the circuit is alive, or dead, or that the apparatus is ready to be switched in. A preparatory signal is thus available for the operator. I should like to make a few remarks about Appendix I and B.S.S. No. 116. British Standard Specifications are intended for practical use, and it is frequently necessary to abandon the strictly scientific in the interests of simplicity and ready comprehension. The circuit-breaker specification, B.S.S. No. 116, is a case in point. Whereas the supply engineer can easily calculate what his short-circuit current will be, the calculation of the probable recovery voltage on his system is a complex business depending upon an enormous number of variables. Consequently it is logical and practical for him to wish to purchase a circuit breaker on the basis of 100 per cent recovery voltage. This is, I think, a sound reason for rating circuit breakers on the basis of system voltage. When it comes to the interpretation of actual test oscillograms, the difficulty lies in obtaining 100 per cent recovery voltage in the test plant. It is often impossible to do anything of the

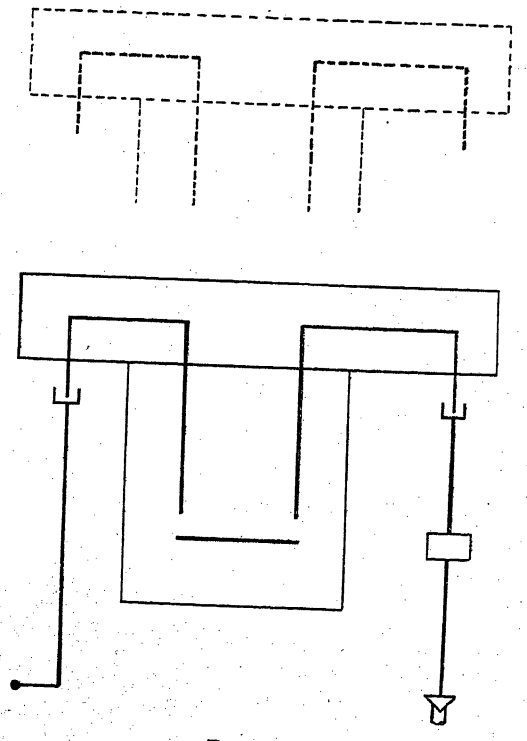


Fig. A.

sort, and allowance must then be made for variations from the desired figure. Unfortunately, so far nobody is in a position to state precisely what allowance must be made for a given departure from a recovery voltage of 100 per cent. We know that in general a high recovery voltage will impose a greater stress on a circuit breaker than a low recovery voltage. Within the last year or two we have realized that a high rate of rise of recovery voltage is probably the more important thing, but the only available apparatus for measuring rates of rise—the cathode-ray oscillograph—is not a test-room device. It can only be used by highly-trained laboratory assistants and even they have yet to develop a common technique, for two men never get exactly the same results from the same instrument. The author showed in one of his slides that during tests the recovery voltage may vary with such factors as the position of the earth connection on the system, and whether field forcing has been used to get heavy currents. I suggest that as a practical way of making B.S.S. No. 116 serve our present purposes, all that is necessary is to define recovery voltage. For this definition I propose that we should take the mean of the R.M.S. value of the first two half-cycles following arc extinction in all three phases, or, alternatively, the line voltage, whichever is the lower. This practical definition will serve until we are able to present a more completely scientific basis for oscillogram interpretation. I should like to comment on the author's suggestions for the future. First of all, with regard to the table on page 319, surely it is more reasonable to state that any circuit breaker, irrespective of voltage, provided it has a single tank per phase and a separated top casting, can be tested single-phase, and equally that any circuit breaker which shares the air space at the top between the three phases must have all its three poles connected when under test. I do not think a voltage limitation is the right way of covering the point. I disagree with the author's suggestion that we should call for a definite recovery voltage. He suggests a figure of 80 per cent, but states that any other value would suit. I think it is far better and far more logical to work back in such a manner that all the figures that are required for computing the results of tests can be read direct from the oscillograph. As we cannot always obtain 100 per cent recovery voltage, it is up to us to find out for the British Standards Institution the basis on which oscillograms can be interpreted, so that it will be possible for all circuit breakers to be compared. I do not think, however, that it will be done by having a standard voltage-recovery figure.

(*Communicated*): When a testing plant is employed it is impossible to predict accurately what the recovery voltage will be, and trial and error must be resorted to if it is desired to get a particular value. Moreover, if the British Standard Specification called for a definite figure, it would automatically preclude the use of field tests except under very unusual conditions. The inclusion in a standard specification of the restriking voltage, of which the rate of rise rather than the amplitude is the important factor, must await the completion of a considerable amount of research and the development of the cathode-ray oscillograph as a test-room instrument. It is surprising to learn from page 320 that the British practice is to insulate the neutral point below 66 kV, and more so to see that it is usual to generate direct from 3 300 to 22 000 volts. I doubt whether this could be called " standard " practice, even on the North-East Coast. Practical considerations of machine and transformer design alone probably control the question of earthing or insulating the neutral of the source of supply. So far as star windings are practicable the neutral should, of course, be earthed if one is attempting to reproduce ordinary working conditions. In addition to the author's proposals for standard tests, it is essential to set up standards for pressure and travel recorders. A lot of new ground has to be broken before a complete revision of B.S.S. No. 116 will be possible, and it is to be hoped that the author's rather bold forecast will not have the effect of holding up the minor but essential changes to the 1929 edition of that specification which are contemplated at present.

Mr. S. Ferguson: With regard to Fig. 38, I believe this record was made with a Collins micro-indicator, and I should like to know what power was being ruptured when it was taken and what was the rupturing rating of the breaker. Would the author be in favour of allowing purchasers to examine the curves of performance of the circuit breakers offered by manufacturers, in order to enable them to make their selection more intelligently? With reference to the tests recorded on page 322, I should like to ask the author what was his experience with the 100 000-kVA breaker, records of which are given, when it was rupturing powers within its rating. All the tests shown were made above its rating, and any defects in performance can obviously be excused on that basis, but I note that at 133 per cent of the normal rating the tank became badly damaged and the top plate slightly distorted. What is the maximum kVA rupturing capacity the author would advocate for direct-operated circuit breakers? I notice that the rather important items of arc length, pressure developed, and rate of rise of recovery voltage on the testing plant, are omitted from the test records. Are these omissions intentional? My next point refers to Fig. 38: although the author states that the tank is designed for 150 lb. per sq. in., no factor of safety is given. The impulse pressure was 950 lb. per sq. in., but there is no proof, of course, that this figure was safe. I should like to correct the impression, which is nevertheless prevalent, about the danger to busbars involved by the vertical type of switchgear. In order to settle the question we have actually carried out rupturing tests on a complete vertical equipment up to nearly 1 000 000 kVA, and, although a very large number of " shots " were made, in no case was there any stress on the busbars. We know that when rupturing tests are being carried out the circuit breaker has a tendency to jump, but in the vertical type of gear stops are provided to take the direct thrust of such upward movement. As regards the horizontal type, in a rupturing test where a complete unit was tested to destruction the cantilever stress due to the tilting of the circuit breaker actually threw the busbars out of position. I disagree that a definite static pressure can be laid down for each tank, corresponding to a certain rupturing capacity, without reference to the design of circuit breaker. It is a question not only of rupturing

capacity but also of the design. Among the thousands of rupturing tests which we have carried out on the modern round-tank circuit-breaker, in no case has a pressure of 350 lb. per sq. in. been exceeded. The pressures which we have measured are very much lower than the figures shown in Fig. 38. I cannot understand the statement (page 302): "Closing on short-circuit is perhaps so rare that in the past it has not been required of circuit breakers in standard specifications." Although an engineer does not always specify it, if he says he wants a certain rupturing capacity he infers, I think, that it must be based on the cycle laid down by the British Standards Institution, which involves the closing of the circuit breaker on the short-circuit. On page 302 the author states: "The problems of the circuit breaker may not be entirely solved by the use of intricate arcing contacts." I, however, believe that they will be so solved. There has been more development in this direction in the last year than there had been in the previous 20 years. We have obtained definite proof that, employing the same outside dimensions of an ordinary plain circuit-breaker, we can double

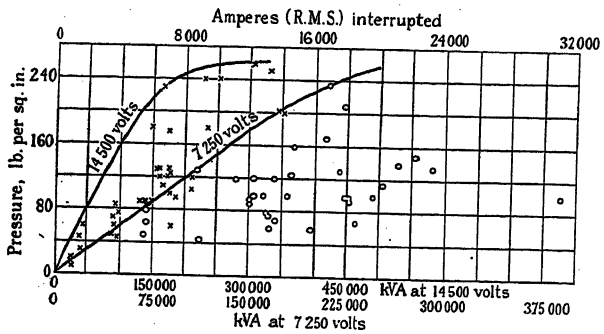


FIG. B.

the rupturing capacity by the provision of arc-control features. I agree with Mr. Coates that the rate of rise of recovery voltage should be specified in the standard performance tests, because that factor may double the stress on the circuit breaker. In America there were considerable misgivings about the differences between circuit-breaker operation on the factory testing plant and in the field. It was not understood why a circuit breaker should always rupture a much greater amount of power in the field than on the test plant, the ratio being of the order of $2\frac{1}{2}$ or 2 to 1. The reason for this difference has been definitely found to be the rate of rise of recovery voltage; as we now know, the operation of the circuit breaker involves a race between the rate of rise of recovery voltage and the rate of rise of electric strength of the space between the electrodes. On a supply system with numerous cables connected to the busbar, the rate of rise of recovery voltage is slow, whereas on the test plant it is rapid. A factor which alters the rating in the ratio 2 : 1 cannot be ignored, and supply engineers have the satisfaction of knowing that any circuit breaker which has proved its rupturing ability on a test plant will have a fair factor of safety on the system. I do not favour rupturing tests with the neutral earthed, as an earthed neutral greatly relieves the stresses. We are testing circuit breakers to destruction in order to find the weakest point, remedying it, again testing to destruction, and so on. Evidence of the enormous forces that are liberated inside an oil circuit-breaker was provided in one of our tests when a channel beam of 3 in. × $1\frac{5}{8}$ in. cross-section was bent up to a deflection of 3 in., and the oil was shot up like a piston from the arc bubble. A weight of about 1·7 tons applied at the centre of the beam is necessary in order to make a bend like the one actually produced in this test. Hilliard, referring to a circuit breaker of this size, suggested that when it is rupturing power at its full rating it develops as much energy as would be liberated by the explosion of 1 lb. of sporting explosive. It would be useful if the Electrical Research Association would investigate this question with a view to the possibility of testing circuit-breaker structures with a definite amount of gunpowder. Fig. B indicates the pressures developed when rupturing definite powers on a typical round-tank circuit-breaker at 14 500 volts and 7 250 volts. The maximum pressure recorded was 260 lb. per sq. in., and the instrument used was sufficiently sensitive to indicate the impulse pressure. I should like to stress the absolute necessity of routine testing of tanks and structures.

Mr. A. R. Blandford: Fig. 21 shows some switchgear which, according to the author, is opening the way to metal-clad gear of much higher rupturing capacity. I do not follow this, because circuit breakers have been constructed with ratings up to $2\frac{1}{2}$ million kVA at 33 kV, and they could just as easily be made to operate at voltages up to 66 kV. The circuit breakers shown in Fig. 21 are of the underhung type, and I think $2\frac{1}{2}$ million kVA is about the highest capacity to which one would care to go with an underhung tank. It may be that I have misunderstood the paper, however, and that the author is really referring to a type (e.g. that shown in Fig. 26) which depends for its success upon mechanical interlocks fixed to the circuit breaker. Such interlocks are, however, very prone to derangement, in view of the heavy mechanical forces set up when rupturing. It would be difficult to rupture charging currents successfully by means of the device shown in Fig. 21, and it might be called upon to do this. I should imagine the design has been produced mainly with the idea of saving space, an idea which can be over-emphasized where outdoor switchgear is concerned. For indoor switchgear, on the other hand, it is important because of the cost of buildings. The advantages of our present outdoor switchgear are: it is accessible, allows of extensions being readily made, and reduces to a minimum the time of shut-down should it develop a fault. Totally-enclosed switchgear is less accessible, and involves shut-downs of much longer duration in the event of the circuit breaker giving trouble. With regard to the question of phase separation, I should like to ask whether the author thinks it desirable even on the smallest types of circuit breakers—rated at 75 000 to 100 000 kVA—to obtain complete phase separation in the tank rather than have common-tank circuit breakers. By a "common-tank circuit breaker" I mean one where the air space and perhaps some of the oil are common to all the phases. I am pleased to see (page 293) that the author includes

the " expansion " switch in the air-blast category. On page 301 it is stated that when selecting a circuit breaker one should allow a safety margin on the rupturing capacity. Is the author prepared, even assuming we come to some definite decision about the interpretation of rupturing capacity, to state what he considers that margin should be? I agree with him that greater precision is required with regard both to the testing of oil circuit-breakers and to the interpretation of the tests. Unfortunately he lapses into the old haphazard way of glossing over the vital few micro-seconds after the zero in which the arc is extinguished. As regards the term " recovery voltage," I prefer to call it " restored phase voltage," and I would point out that it is of normal frequency. What I consider to be the recovery voltage is the high-frequency rapidly-rising overshooting voltage that occurs across the contacts of the circuit breaker immediately after the zero in which the arc is extinguished, and this is controlled by the characteristics of the circuit. To a very large extent the controlling factor is self-capacitance, as was mentioned by Mr. Ferguson. The frequency of the recovery voltage is very important. I do not understand Mr. Ferguson's ratio of 2 : 1 in this connection, because oscillograms which I have studied show that the circuit breaker is not affected by the normal-frequency voltage whilst it is rupturing. The recovery voltage is the only one which affects the circuit breaker at this time. It is easy to understand that as the circuit-breaker contacts are opening, current ceases to flow in the arc at each current zero. The particular current zero at which the arc is extinguished depends upon whether the voltage at the current zero rises sufficiently fast to break down the electric strength of the arc path; if it rises rapidly enough the arc is kept floating. The action of rupturing, therefore, resolves itself into a race between the rate of rise of recovery voltage and the rate of recovery of the electric strength of the arc path. The author suggests in Appendix I that we should have a standard circuit but take no notice of this recovery voltage; in other words, he wishes to rate the circuit breaker on the normal-frequency voltage. I do not understand why, if we have a standard circuit, standard capacitance, standard characteristics of generator, standard reactance, standard resistance, and an almost constant frequency, the rate of rise of recovery voltage should not be regarded as one of the standard test conditions. The oscillograms shown in the paper give no indication of the self-capacitance or the characteristics of the author's standard circuit, nor does he offer any information regarding the high-frequency voltage to which I have referred. I think we shall have to adopt a standard circuit, as the author suggests, but a record will have to be made both of this standard circuit and of the recovery voltage. I agree with Mr. Coates that the latter will have to be recorded by means of the cathode-ray oscillograph. All we need to be sure about is that when the test circuit has been accurately standardized, a circuit breaker which passes the test will stand up to the worst conditions of recovery voltage which it will meet with in practice.

Mr. W. R. Cox: Referring to Fig. 58, which illustrates methods of safeguarding telephone systems, it seems to me to be of great importance that the spark-gaps referred to for what we may call " initial " protection (e.g. protection against breakdown of a current transformer) should be placed as near as possible to the current transformer. If it is any considerable distance away, the damage which is done by such a breakdown will spread to other control circuits, and is almost certain to get through, by other channels, to the Post Office equipment. I mention this point because in many cases it is somewhat difficult to add these spark-gaps after the design has been settled. Referring to system control, it seems to be present-day practice to concentrate indications at a central point, whence by means of telegraphs or telephones the control engineer directs the carrying-out of various operations in remote power stations or substations. For this purpose a supervisory system is installed, which is often so designed that a slight addition will convert it from an indicating system into a true control system. This change will effect a great saving of time and will probably lead to fewer operating mistakes. Developments of this kind ought to be put in hand in the near future, as the capital outlay will be comparatively small and the advantages gained considerable. On page 316 the author refers to two types of remote-control gear, one the " supervisory control " gear which is based upon the telephone-relay type of apparatus, and the other the " centrovisory control " gear which has been developed along separate lines. The former has many advantages over the latter. In the first place, it is more flexible, secondly it is very much quicker in operation, and thirdly the type of control board developed for the centrovisory system seems to me to be rather clumsy owing to the fact that the indicating lamps and indications generally are in circular form. Finally, I wish to refer to the application of supervisory switchgear to circuits of very much smaller power. If a large power system is to be useful, a very large number of secondary circuits of lower voltage and lower power must be employed. These all need a certain amount of control, and in this connection a simple and inexpensive form of supervisory gear is very useful. At least one such system has been developed using two pilot wires which can be looped in tandem into at least 30 stations, and can control 10 separate operations in each station. These operations can be telephony, switch opening and closing, metering, and initiation of tap changes for voltage variation or load distribution, or the control of induction regulators (which serve very much the same purpose as tap-changing gear). The time is now ripe for these small schemes to be considered seriously, bearing in mind that we hope to increase the use of the " grid " by the extension of the lower-voltage transmission systems, thus making electric power available to a larger number of consumers.

[This discussion was adjourned until the 3rd March (see page 334).]

ADJOURNED DISCUSSION BEFORE THE INSTITUTION, 3RD MARCH, 1932.

Mr. E. B. Wedmore: In the paper* on this subject which I read before the Institution 14 years ago I suggested that wherever supply depended on any one busbar, that busbar should be duplicated. Although my suggestion was at that time regarded by some as extravagant, I notice that in the designs now set before us there is ample provision of duplicate busbars. However, I am still uneasy about the proximity of the main and alternative busbars in many of these designs. At one time I was entirely opposed to the use of such concentrated types of switchgear in important power stations, not because the resultant economy was not good in itself, but on account of the great engineering difficulties of developing such a design in a sufficiently reliable form. The experience of the last 14 years, however, has shown that such apparatus can be made to function satisfactorily in large power stations. In several of the designs shown, and particularly those where the main circuit-breaker is duplicated, there would be little difficulty in inserting a substantial wall between the busbars and thus obtaining much more complete isolation at a very small additional cost and with little additional space. Where the voltage is high the duplication is better justified owing to the reduction of the number of insulators necessary, these being a very costly part of the complete structure. In 1918 we were considering the use of reactances to limit the amount of power with which the switchgear had to deal, and it was concluded that manufacturers were able to supply switchgear to meet any conditions at that time obtaining in service. Mr. Ferguson and others are doubtful whether all the circuit breakers now on the market are capable of standing up to their ratings, and I agree that in their performance there is an element of uncertainty which we should try to remove. I am concerned also at the high cost of circuit breakers as part of a complete system. The necessary six insulators for the incoming and outgoing terminals of a large circuit breaker account for a good deal of the capital outlay, but there is still a considerable margin for economy in the cost of the remainder of the structure. Manufacturers are now aiming at producing more reliable types, which shall be more uniform in operation and yet prove less costly. We ought not to have to provide large structures for withstanding high explosive forces; it should be practicable to confine such forces in a small structure inside the circuit breaker and so arrange the parts as to secure complete control of the arc, the arc products, and the conditions under which the circuit is prevented from re-establishing itself. There is another factor, however, in regard to which there is room for improvement in practice. Notwithstanding the reactance in the different parts of the grid system, there never was a time when so many supply engineers were uneasy as to the rupturing capacity of their existing switchgear and of the equipment which they will have to install when the grid comes into full operation. There will be a great market for circuit breakers having 2 or 3 times the present rupturing capacity without any increase in the present dimensions. Most manufacturers are faced with the difficult task of proving and developing the new types of circuit breakers that the market requires. Many tests under working conditions are necessary, and these tests can only be made where heavy plant of adequate capacity is continuously available. The Electrical Research Association has been advocating the provision of such plant in this country for general use since 1924. We realized at that date that the situation with which we are now faced was bound to arise. British engineers have to produce their own new designs of circuit breakers to compete with the new types now being prepared for the market in all parts of the world. This matter is of equal importance to the supply industry, because the buyer desires to have an assurance from some independent authority as to the performance of the circuit breakers which he desires to purchase. As regards the type of test to be employed, it will not be sufficient merely to have agreement between the buyer and seller as to the nature of the test. We must be satisfied that the test is sound in itself. Turning to the oscillograms shown in Figs. 69 to 74 (Plates 2, 3, and 4), there is one feature as to the interpretation of which there is no general agreement. I refer to the phenomenon of the recovery voltage which appears in the several phases during 2 or 3 half-cycles after the circuit is broken. This depends mainly on the properties of the test circuit. Dr. Slepian is responsible for the broad conception that we can equate the recovery of the voltage with the recovery of the electric strength of the gap in the circuit breaker. The Electrical Research Association has also been engaged on a study of this phenomenon and has discovered some factors which do not seem to have been dealt with in the papers published hitherto. The quantitative effect of changing the character of the testing circuit varies according to the type of circuit breaker under test. The author raises the question of the effect of the arc on the properties of the circuit where the arc occurs and which may contain protective gear. This problem has been referred to the Electrical Research Association, but we have so far done only a little theoretical work on it. We feel that the presentation of the matter and its application would be simplified if the author's results were expressed in terms of the voltage-drop per unit length of the arc.

Mr. T. W. Ross: As regards Appendix III, I should like to assure the author that his fears as to the reliability of impedance relays are without justification, since relays of this type have proved very effective and reliable both in this country and abroad. I would, however, put forward a plea for greater simplicity in protective gear than is sometimes displayed to-day. Protective devices are called upon to function very infrequently, and if they are complicated or if they depend for their action upon a combination of devices which are in turn dependent upon each other, it is bound to be more difficult to maintain them in efficient operating condition. The reactance relay is more com-

* "The Control of Large Amounts of Power," *Journal I.E.E.*, 1918, vol. 56, p. 289.

plicated than the impedance type, and I feel that one should give very careful consideration to the question of simplicity before embarking upon any of these theoretically more perfect schemes. Turning to the pilot-wire type of protective gear, there is a statement on page 310 that the author's split-pilot system is provided with a tuning arrangement to prevent incorrect operation on the abnormal frequencies. Although it has been supposed that some cases of incorrect operation of the older Merz-Price type of protection were due to abnormal frequencies at times of short-circuit on some other part of the system, I would suggest that probably the cause was not so much an abnormal frequency as the fact that the short-circuit current in its earlier stages is of an asymmetric nature and gives rise to unidirectional impulses. It is practically impossible to balance these out in current transformers, and any protective gear which utilizes an electromagnetic relay may be subject to operation from d.c. impulses. In the Translay gear, for which I am responsible, the relay is of the induction type and is therefore immune from operation on direct currents. It is probably for this reason that the Translay relay has been so successful under very onerous conditions, and perhaps the tuning condenser which the author has introduced also bypasses these d.c. impulses. In any case, the acid test of immunity from incorrect operation must be the test of service. The type of protective system shown in Fig. 56, in which a high-frequency carrier current is injected into the circuit cables, is being tried on a single section of the British "grid." The author places a rejector at each end of the phase to transmit this high-frequency current, and it occurs to me that it will be necessary to put rejectors in all three phases if this carrier current is to be applied to more than one section of the network. The electrostatic capacitance coupling between the phase in use and the other phases will probably transmit the high-frequency current through to the other sections, and cause operation of the locking devices when they are not required to operate. It would be of interest to know whether the author has considered the possibility of this, and whether he considers such a scheme capable, without the addition of such rejectors, of being applied to several sections of the same network. Carrier-current protection suffers from the disadvantage that a comparatively complicated apparatus incorporating a hot-cathode valve has to be employed. The fact that the hot-cathode valve has only a limited life also necessitates relying on the human element to replace it, and although signals may be given when a valve is burned-out it is not always convenient to have attendants on the spot to notice the signals and replace the valves. On page 299 the author suggests the use of a condenser coupling instead of a potential transformer for measuring the potential, and states that the condenser coupling is more reliable than the transformer. I do not agree, because I feel sure that a good modern potential transformer with its windings so designed as to equalize capacitance stresses will be in every way as reliable as a condenser coupling. In the first part of this discussion Mr. Cox raised the question of supervisory control systems, and mentioned that the new method for which the author has coined the name of "Centrovisory" control is less flexible than a system using the standard telephone apparatus. In my opinion the automatic telephone apparatus is now extremely reliable, and to substitute for it something which is less flexible is a very doubtful advantage. Supervisory control can only give of its best if it is introduced in the form of a mimic diagram, and centrovisory control does not lend itself so easily to such a diagram as does the automatic telephone apparatus. The latter has the advantage that it is already being manufactured by mass-production methods.

Mr. J. R. Wilkinson: The first point I should like to take up is the comparison in the paper between the horizontal and vertical types of isolation in switchgear. Figs. 24A and 24B do not afford a true comparison. In the vertical type there are two independent circuit breakers, whereas the horizontal gear has only one circuit breaker with oil-immersed selector switches, and this does not give the same scope or range of operation. The vertical arrangement has an advantage in that the number of insulators is reduced. Mr. Wedmore remarked that he was rather concerned about the extreme proximity of the two sets of busbars, and in this connection again the vertical gear is the better because it does not involve placing the busbars one above the other, as in the normal horizontal construction. My next point refers to metal-clad switchgear having internal isolation in the circuit breaker (Fig. 16). The author indicates that this may have some advantages as compared with the orthodox type of vertical isolation, but it seems to me there are two very considerable disadvantages. In the first place, every time the circuit breaker is plugged on to the busbars six joints have to be made in the top plate. These joints must be gas- and oil-tight under a pressure of several hundred pounds per square inch when the circuit breaker is functioning under short-circuit conditions, and it is very difficult to make a joint of that description simply by winding the bushing up against the top plate. The second serious disadvantage is in case of damage to the circuit breaker under short-circuit conditions. The first slide which I propose to exhibit shows the effect of explosive forces produced under short-circuit conditions on a circuit breaker which had been tested to destruction. In this case the stout channel-iron beam just under the top plate has been bent upwards by the force of the oil, and to do this requires a force of about 2 tons. If the isolating mechanism is inside the circuit-breaker tank, a deflection of the members caused by the explosive forces may prevent the station engineer from isolating the circuit breaker from the busbars. My second slide, taken from a cinematograph film, shows an old-type rectangular-tank circuit-breaker at the moment of bursting under short-circuit stresses. It emphasizes the absolute necessity, both for the sake of the safety of the operator and for that of the continuity of supply on adjacent circuits, of the outer carcase of the circuit breaker being one of the strongest points in its construction. Considerations of this kind have led to the development of the circular tank with a domed top plate and dish bottom: if this construction is adopted and the other features are carefully designed, the carcase of the circuit breaker is found to be one of its strongest portions.

All the damage is then confined to the inside of the circuit breaker, instead of spreading to adjacent circuits or injuring the operators.

Mr. B. H. Leeson: Some years ago I carried out a series of explosion tests in a large dug-out to ascertain the ability of circuit breakers to withstand the pressures set up within their enclosures during the process of breaking short-circuits. It was thought at that time that the pressures developed would consist of an initial impulse pressure of high value associated with a sustained pressure of much lower value, and for this reason each explosive charge consisted of a blend of high-explosive and ordinary gunpowder. The number of charges exploded within an enclosure was increased on each successive test until destruction occurred. The pressures were recorded by devices similar to those used to record explosive pressures in gunnery research, and impulse pressures as high as 5 000 lb. per sq. in. were utilized. The metal enclosures were tested first for their ability to withstand a steady hydraulic pressure, and subsequent explosive tests indicated that the enclosures could be quite safely subjected to momentary pressures of 15 to 20 times the value of the steady hydraulic pressure. Having compared these tests with the time/pressure curve of Fig. 38, I consider the value of 10 given by the author as the ratio between the steady and impulse pressures to be well on the safe side. The subsequent satisfactory behaviour of the circuit breakers, when tested on a short-circuit test plant, was due in no small measure to the knowledge gained from the earlier explosive tests. A modern short-circuit test plant should be capable of testing standard circuit breakers ranging from 1 500 000 to 5 000 kVA at the standard rated voltages given in B.S.S. No. 116—1929, and I should like to consider whether the author's proposals as set out in Appendix I for testing and service conditions usually associated with the duty of standard circuit breakers. The duty imposed upon a circuit breaker under test depends (*a*) upon the normal frequency, and (*b*) the oscillatory characteristics of the test circuit (see Fig. C). With reference to (*a*), the specified rated voltage, making current, breaking current, power factor, and recovery voltage at normal frequency, can be obtained by suitable adjustments of the generator field, reactors, and resistors, so as to impose the desired normal-frequency duty upon the circuit breaker. With reference to (*b*), the duty imposed upon the circuit breaker by the severity of the rate of rise of restriking voltage is dependent upon the natural oscillatory frequencies of the test circuit and the normal-frequency recovery-voltage. When testing a large circuit breaker for use in service in close proximity to generating plant, the connections between the circuit breaker and the source of the short-circuit power at the test plant should be of the shortest possible length, so as to ensure a high rate of rise of restriking voltage. When testing a small circuit breaker, a larger amount of reactance must of necessity be included in the test circuit to reduce the normal-frequency short-circuit current to the desired amount, with the result that the natural oscillatory frequency, and with it the rate of rise of restriking voltage, is automatically reduced, although the self-capacitances of the test circuit remain virtually constant. The order of variation in the rate of rise of the restriking voltage (in volts per microsecond) is shown by Fig. D, in which the four ordinates are arbitrary and are intended to represent circuit breakers of four different ratings used under correspondingly different service conditions. The black bands on the ordinates indicate the order of magnitude of the rate of rise of restriking voltage, which is shown thus in order to include possible differences in values arrived at from calculations and measurements made by different observers on different test plants and cathode-ray equipments. Ordinate 1 represents a large circuit breaker, Ordinate 4 represents a small circuit breaker, and the other two ordinates represent intermediate severity in restriking voltage for other circuit-breaker ratings. The diagram is not intended to represent approved numerical values of restriking voltage, but is included to illustrate the point that what is

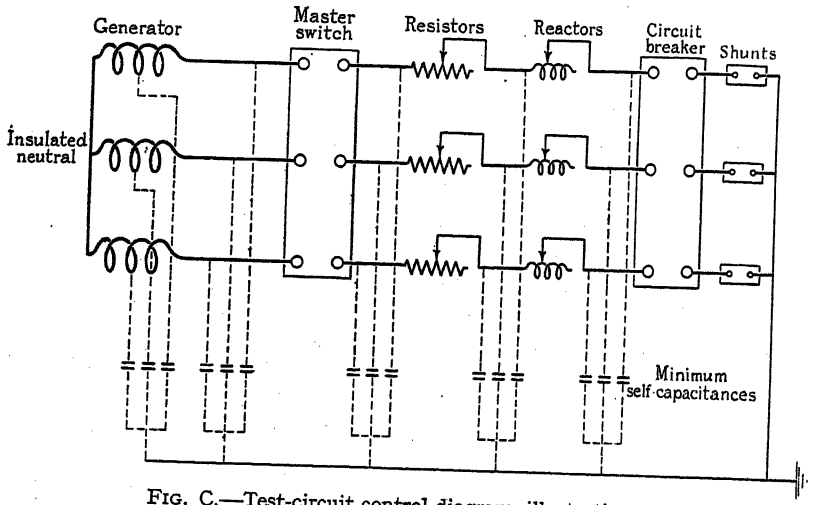


FIG. C.—Test-circuit control-diagram, illustrating:—
(*a*) The adjustability of the severity arising out of normal-frequency characteristics.
(*b*) The inherent dependence on (*a*) of the severity arising out of oscillatory-frequency characteristics.

required is the standardization of a range of rates of rise of restriking voltage for various values of short-circuit currents, and not the standardization of a universal rate of rise of restriking voltage, which, if low enough to be suitable for a small circuit breaker, would be absurdly easy for larger circuit breakers, and conversely, if high enough to be suitable for a large circuit breaker, would be physically impossible to obtain in tests of smaller circuit breakers. In my opinion the author's "Proposals for Standardized Performance Tests" do legislate for the required range of rates of rise of restriking voltage (see Fig. D), because his conditions implicitly control the order of magnitude of the restriking voltage under different service conditions by reason of the necessity for including in the test circuit (Fig. C) definite values of inductance and resistance to comply with the specified standard conditions corresponding to the size or rating and use of a circuit breaker in service,

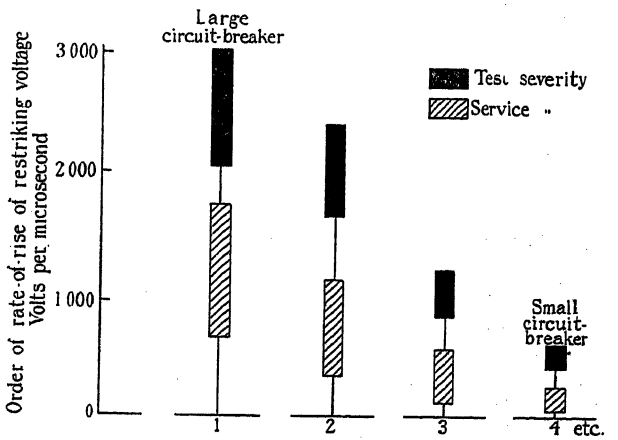


FIG. D.—Restriking voltage severity-diagram, illustrating:—

(*a*) Ranges of test severity and service severity, which are inherently dependent upon values of short-circuit current.
(*b*) The reduction in severity of service conditions as compared with test conditions.

and by reason of the small self-capacitances of the test circuit remaining virtually constant in value and appropriate for the large circuit breaker. Another fact which Fig. D is intended to illustrate and which is legislated for in the author's proposals (Appendix I) is that the severity of the standard test circuit is automatically greater than that of the conditions of service it is intended to represent. For example, a large 3-phase circuit breaker of a voltage rating below 66 000 volts would be tested with the generator neutral of the test circuit insulated, which would give a normal-frequency recovery voltage across the poles of the circuit breaker on the first phase to break 50 per cent greater than if the neutral point of the generator were solidly earthed, and would result in a restriking voltage of the order shown by the black band on Ordinate 1. In service, however, there are two primary easements. The first arises from the usual practice of earthing the generating plant through a comparatively low resistance, which gives a much lower recovery voltage on the first phase to break; and the second lies in the greater electrostatic capacitance of the length of cable or overhead line between the circuit breaker and the source of power and that of the network as a whole, as compared with the small self-capacitance of the test circuit. The rate of rise of restriking voltage for the conditions of service is therefore lower than that of the corresponding test conditions, and its order of magnitude is shown by the band with section lines on Ordinate 1. Similar easements apply to the small circuit-breaker rating of Ordinate 4, but they are more pronounced because of the greatly improved power factor and the further reduction in the rate of rise of restriking voltage produced by the capacitance, inductance, and resistance, of the comparatively long cables or overhead lines connecting the small circuit breaker to the source of larger power supply. In service, the small circuit breaker is likely to be subjected to a normal-frequency recovery voltage in excess of the minimum of 80 per cent specified by the author; but here again a similar increase would automatically result on the test circuit because of the small amount of power taken from the generating plant in proportion to what it is capable of developing for testing the large circuit-breaker ratings. Research is required to determine the numerical values of the rate of rise of restriking voltages that exist at different points on typical supply networks under varying conditions, with the object of standardizing a minimum range of numerical values of restriking voltage under which to carry out standard performance tests. Although some research is in progress, it is likely to be many years before this object is attained. This important study also includes investigations of the degree to which the behaviour of different types of circuit-breaker constructions is affected by different rates of rise of restriking voltage. In my opinion it is premature at this stage of progress to include numerical values for restriking voltage in any proposals for standardized performance-tests. I would therefore make a plea for the early adoption of the author's proposals, which specify conditions of severity for the test circuit well in excess of the corresponding conditions of severity in service, and in this practical way form the much-needed standard by which circuit breakers may be judged.

Mr. J. P. Cranmer: I am surprised to find that the paper makes no reference to the multi-break contact oil circuit-breaker, and I should like to know whether mention of it is omitted because its performance has not come up to expectations. Passing to the question of busbar capacity, I am glad to see that the author gives some current-density figures (page 301), because one has considerable difficulty in impressing on some people the necessity of running at these low densities when the current rating of the busbar exceeds 2 000 or 3 000 amperes. Referring to Fig. 76, I presume the author has in mind the arc on a 132-kV line, and I do not quite see why an arcing distance of 6 ft. is taken there. I should have thought a more practical distance would have been the length over a string of insulators (about 42 in.); this would make a big difference to the arc resistance. Moreover, the fact that the curve is based on low current values makes it a little misleading, because on 132-kV protective gear the minimum operating current would in any case be of the order of 200 amperes. If only higher values than this were employed in plotting the curve, the sharp bend at 200 amperes would be

eliminated. Reducing the arc resistance in the ratio of 6 ft. to 42 in. shows that although the arc resistance does affect the impedance type of protective gear, its influence is not so important as theoretical considerations would lead us to expect. This point, combined with the more robust construction of the impedance relay, should be considered in a comparison of the two types of protective gear. On page 299 the author advocates the use of capacitance transformers rather than the ordinary potential transformers. In a large number of the shut-downs caused by incorrect operation of protective gear the trouble is due not to the high-tension apparatus but to its associated low-tension equipment. Far greater care is usually given to the high-tension apparatus than to the insulation or design of the secondary connections and apparatus, and this is where the capacitance bushing is at a disadvantage as compared with the ordinary potential transformer. Our present design of potential transformer is as reliable as the capacitance transformer; the former has the advantage that it involves no condensers and smoothing arrangements to complicate the secondary circuit and cause trouble under service conditions. Furthermore, the potential transformer has the greater output and accuracy.

Mr. S. C. Bartholomew: I wish to refer to a matter which is dealt with on page 313 and also in Appendix IV, namely the steps to be taken where Post Office lines are used for the subsidiary service associated with power-circuit operations. The author indicates that the metallic sheathing of the telephone cables should not come within 50 yards of the power station, and should be separately earthed there, these precautions being necessary owing to the potential gradient which is set up on the occurrence of faults on the power system. I should like to know how this figure of 50 yards was arrived at, and I should welcome details of the tests which have apparently been carried out by the author and those associated with him. I notice that the word "station" is used: a "station" may be a very extensive building, and perhaps "station earth-connection" is intended. A factor of some importance may be the presence of gas and water pipes and the metallic sheathings of power cables. Is it not likely that in certain circumstances these pipes and cable sheaths may form an indirect and undesirable connection with the station earth-plates, and so extend the danger area? We have had trouble with Post Office cables and circuits that might be attributed to this rise of potential gradient on the occurrence of faults at power stations. In some cases, particularly in districts where a great deal of trouble from lightning occurs, the protective devices on the telephone circuits have operated, and cables leading into a power station have actually been burned through in the ground, the lead sheathing being melted. There has, however, always been some difficulty in ascertaining whether the trouble was due to a fault on the power circuit or could be attributed directly to lightning. It is possible that the lightning produced a fault on the power circuit, and that this in turn caused damage to the telephone plant. A consideration of all the relevant facts, however, suggests that the cause of the trouble has been the rise of potential in the soil in the neighbourhood of the power station.

Mr. J. F. Shipley: I should like to refer to the operation of a telephone system installed directly beneath the 33-kV power lines of an extensive transmission network in the tropics, where lightning occurs every afternoon from 1 p.m. to 6 p.m. for 6 months in the year. The telephone system is of great importance owing to the necessity of avoiding the effect of sudden floods and stoppages on the mining plants connected to the network. It is protected by drainage coils, transformers, lightning arrestors, vacuum gaps, and fuses, and with it we have been able to maintain permanent and clear communication during, and in spite of, the lightning. Even if—as has already happened—a 33-kV power line falls on to the telephone line while men are speaking, no harm results beyond the blowing of a fuse. We have trained the native linesmen to be prepared to replace the fuse at once in the event of an interruption. A careful record is kept of all faults, but contrary to expectation these have been exceedingly few in number. Were the system unprotected an earth fault on the network would, owing to the high specific resistance of the earth, give rise to high voltages on the telephone line which might injure the apparatus and cause shock to the operators. We have experienced some insecurity owing to our relay batteries being of the alkaline type. The electrolyte has to be renewed annually, and this has made us consider very seriously whether we shall install such batteries in future. Even our white engineers, although they are told to put special electrolyte into these cells, fill them up with acid!

Mr. W. A. Crocker: I am disappointed that no figures are given in the paper which would help the power engineer or purchaser of switchgear to decide how to allow for the effects of power factor and recovery voltage. Assuming a power factor of 0·5 and a calculated short-circuit kVA of 300 000 on a 100 000-kVA system, is the author able to state the breaking capacity of the switchgear required? Can the factor of 2 to $2\frac{1}{2}$ referred to by Mr. Ferguson for test results compared with field results be applied in such a case? I think it is time that breaking-capacity tests were undertaken by an independent authority, as a great many "mushroom" firms are now marketing switchgear and the purchaser cannot decide from the technical data whether it is properly designed. I agree with the author as to the advisability of earthing cables through the switch, but I would point out that operating staffs need help in this procedure. So long as it takes several minutes to apply the earthing device, and until it can be done with safety, operating engineers will neglect this precaution. Manufacturers have not paid sufficient attention to this matter; in many cases it is dangerous to apply the earthing device, as in order to do so it is necessary to uncover the isolating-contact orifices and presume the contacts to be dead. In one instance which occurred within the last 2 years it was considered satisfactory by the manufacturer to remove the circuit breaker from its rack by means of a truck in order to apply the earthing device. I should like to stress the need for simplicity in switchgear, because delays often arise when several manufacturers' switchgear is used on one system and three or four interlocks of different types are incorporated in each.

Mr. J. W. Rissik: From the author's statements on pages 292 and 293 I gather that he regards the expansion switch as a particular type of air-blast circuit-breaker. I do not think this view is correct: the expansion switch is different from the air-blast circuit-breaker in that it is the only switch in which the gas generated by the arc is subsequently expanded adiabatically. In the ordinary air-blast circuit-breaker a blast of air is merely trained on to the arc in order to scatter it. In the expansion circuit-breaker the arc is struck under water, and when the two contacts separate the steam which is formed cannot escape from the expansion chamber; but as soon as the contacts draw apart still further the pressure is suddenly released and the steam expands adiabatically, with the result that a very rapid temperature-drop takes place in the superheated steam, which immediately condenses. It can be shown that when an arc is ruptured in a saturated vapour the gases are rapidly de-ionized, so that there is no tendency for the arc to restrike. The free adiabatic expansion causes such a rapid temperature-drop that de-ionization occurs before the recovery voltage has time to reach a value high enough to restrike the arc.

Mr. E. O. Taylor: The principle underlying all the circuit breakers which have been described in the paper and by speakers in the discussion is to build them in such a way that they will withstand any explosion that may occur as the result of the liberation of the arc energy. It seems to me that a better way of approaching the subject is to do as the last speaker suggested, and de-ionize the gas between the contacts, thus preventing the arc from re-igniting after it has gone out at the end of the first half-cycle. The expansion switch and one or two of the circuit breakers mentioned by the author are based on this idea. I should like to ask whether it is possible to use the grid-control rectifier as a switch. This device makes it possible to prevent the arc from re-igniting after the end of a half-cycle, and with a little modification it might be made suitable for use as a switch. In this connection, the grid-control rectifier and various other pieces of apparatus are being developed with a view to utilizing high-tension direct current for transmission. Have the manufacturers considered the question of switching high-voltage direct currents, or would all switching have to be done on the low-voltage side?

Mr. P. F. Grove: I should like to point out that there is a difference between rectangular-tank and round-tank circuit-breakers, in that it has hitherto been understood, at any rate in the earlier square-tank designs, that there ought to be definite separation of phases where three phases are in one tank, and for that purpose steel barriers have been interposed between the phases. In the case of the round-tank circuit-breaker definite welded-in partitions between the phases are unsuitable, owing, I believe, to the unequal distribution of oil volume and bad distribution of stresses. Is the design of the round-tank circuit-breaker such that the pressures in it are equalized and barriers therefore become unnecessary? On putting switchgear into service it is often found that moisture in the oil has found its way to the bottom of chambers, other than the oil switch tanks, and formed a small pool of water which has seriously decreased the clearances of certain insulators. Manufacturers should therefore take special precautions to allow for moisture being drawn off from the bottom of such chambers. It might be advocated that works tests should be carried out with oil of low electric strength. Generally speaking, works tests are carried out with oil of the highest electric strength, and it might serve a useful purpose for the designers to make a test using oil of 20-kV electric strength. The use of fibrous materials inside circuit breakers may result in fibres mixing with the oil, and if moisture is present the resultant oil will tend to break down far more easily than if mixed only with colloidal carbon, which has up to the present been regarded as one of the most common causes of the breakdown of oil, owing to the difficulty of its extraction. It is further of interest to note that there is considerable danger in using semi-fluid compound fillings owing to the difficulty of ensuring sufficient freedom from moisture and fibres.

Mr. W. E. Highfield: The breakdown of switches may be divided into two classes, those in which there is a total destruction and those in which the damage can be repaired in a reasonable time. In my opinion minor mechanical faults occur far too frequently. Switchgear has become so large and the mechanical forces involved so considerable that the mechanical parts are similar in design to those associated with the old low-speed engine. Twenty or thirty years ago we had a fine body of firms able to produce designs that would work continously without breakdown; the Lancashire mill engine and the marine engine were of this type. The operating gear of a Corliss engine involves mechanical devices very similar to the operating mechanism of an oil switch, with the exception that whereas the engine gear worked continuously the switch mechanism must be able to work at any moment between long rests. I think that greater attention should be paid to making the mechanism between the first point of mechanical movement and the mechanism in the tank, completely immune from failure.

(*Communicated*): The paper makes clear the high efficiency to which the design of the oil circuit-breaker has been brought. It is interesting to recall the days of the air-break switch, barely thirty years ago, when shift engineers were usually equipped with a short piece of leather belting to " swat " out the arc. Although the types of circuit breakers mentioned in the paper differ in various ways, they have one mechanical feature in common, namely, that the switch is thrown out by a spring which is compressed by a full-power solenoid. This fact is rather surprising in view of the many mechanical methods that exist for producing quick movement of parts, e.g. hydraulic and compressed-air systems. I should have thought that hydraulic movement would certainly have been explored, since the medium of oil is already present. There are few mechanical devices more sure in action than the hydraulic ram, which is simple to control, robust, and capable of withstanding severe weather conditions. Compressed air is widely used in railway work for the operation of points and contactors of all sorts, and it has been proved to be thoroughly robust and reliable. A good argument against the use of hydraulic or air systems is that there

are already sufficient services on a substation. On the other hand, the fact that large and costly switches controlling important supplies are far too often put out of service by minor mechanical defects makes an improved design imperative. Having made a suggestion that might seem to imply more complication, I must now plead for simplicity and low cost. As the field of electric supply extends, the supply authority has to go further afield to obtain additional load and has to spend more and more capital to reach it. There is a definite limit to the economies that can be gained by increased efficiency of generation and transmission, and it is a moot point whether we do not now invest too much capital in equipment for obtaining improved efficiency. If cheaper electricity is to be supplied one of the widest fields for gain is in the reduction of capital cost. The largest single item in the cost of a unit of electricity is that of distribution, but considerable economies could also be effected by a reduction in the cost of making a connection to the high-tension lines. A relief in this direction would be of immense assistance to the national "grid" system. It could only be achieved by a reduction in the cost of switchgear. I should imagine that rather more than half the net cost of a large oil switch goes to pay for the material, the rest being assigned to labour and "on cost" charges. By far the largest single item of cost is the pair of bushing insulators in each phase tank, and at the moment this is the only item that offers possibilities to the scientist and engineer in the way of reduced cost. The economy to be achieved in this direction is, however, not large. Any considerable reduction in the cost of a high-tension connection must therefore be sought in a different method of application of switchgear, and there is a possibility in this direction if advantage can be taken of the reactance of the transformers in the total circuit between the high-tension line and the consumer. I raise this point in order to make clear the desirability of reducing the switchgear breaking-capacity after the high-tension connection. For example, if the switch at the high-tension connection is rated at $1\frac{1}{2}$ million kVA, the switch on the secondary side of the transformer may be of $\frac{3}{4}$ million kVA capacity. We want some safe method of connecting to this circuit a system with switchgear of only 50 000 kVA capacity. This suggestion for keeping down capital costs has perhaps not received all the attention it deserves. Instead we have tended to raise the standard of low-capacity switchgear. Confusion will ensue if this path is pursued, because more and more small systems desire to be linked up with larger systems, and they must be so linked up if the national system is to have full scope.

Mr. G. E. Moore (*communicated*): The paper is regrettably lacking in information with regard to the instruments which are incorporated in modern metal-clad switchgear. It has yet to be generally appreciated, first that the integrity and intelligent use of instruments can have a marked beneficial effect upon the internal economic working of a supply undertaking, and secondly that the metering in consumers' premises safeguards the revenue of the undertaker. A low-tender metering equipment of poor design may through lost revenue ultimately be the most costly. From the cursory way in which the author deals with the subject of transformer accessibility (page 290) it is obvious that he does not regard the maintenance and life of the instrument transformers as of particular moment. It has yet to be shown, however, that transformers remain unaffected no matter how they are mounted. Moreover, doubts occasionally arise as the result of disputed accounts and through ageing of the equipment; in such cases, for the purpose of complete practical assurance, the performance should be checked. In addition, ratio checks every 10 years are advantageous. Sometimes it is possible to isolate a set of current transformers and test them by means of a neighbouring low-voltage source. Again, temporary current transformers may be inserted elsewhere in the circuit. In other cases the potential transformer may be tested with a portable potential transformer by direct access to its primary fuses or power-transformer terminals; or the chambers may be withdrawn and taken to testing headquarters. Cubicle and truck-type switchgear is not old-fashioned, at least as regards accessibility. Makers do not appear to appreciate the necessity for thorough tests of metering equipment both before it leaves the works and on erection. Much expense and delay would be avoided if all primary and secondary fuses were made accessible. Wherever possible, the use of plug connections should be avoided.

Mr. H. Trencham (*communicated*): In examining the numerous suggested switchgear arrangements to which the author refers, I am struck by the number of attempted innovations for which the only justification appears to be a desire to do something differently. In oil-filled switchgear it is certainly a step forward to have rendered current transformers more readily accessible. A thoroughly satisfactory arrangement for potential transformers, however, is not so easily found. A feature which would be appreciated, especially in the export market, would be an easier method of arranging for extensions or modifications. It is possible to attach too much importance to the weight of the circuit-breaker unit when considering the question of isolating the latter by moving it from contact with the busbars. The switchgear engineer is a little slow in taking advantage, for his own purposes, of the wonderful flexibility of the power which he controls. The actual power consumption necessary for carrying out isolating operations electrically would be small, and it is surely no disgrace to make use of electric motors for this purpose. Simplicity is the guiding factor in the matter of isolation. Many engineers attach great importance to the actual visibility of the isolating process, and in this respect movement of the circuit-breaker unit—whether horizontal or vertical—is simple. An isolating and earthing switch was provided in the first 132-kV oil-filled enclosed switchgear system, but it was also specified that the isolator unit should be made suitable for complete withdrawal on plug-and-socket contacts. I do not advocate such duplication, and it was probably employed solely as a precautionary measure on what was really a piece of bold pioneering work. The author's treatment of oil circuit-breaker operation is very brief and does not do full justice to the advances which have recently taken place. I have lately noticed a tendency to criticize the British switchgear engineer for not

offering such devices as gas-blast and expansion circuit breakers. In a recent article* I have attempted to sum up the pros and cons of recent developments in a.c. circuit-breaking, and to prove that the improved oil circuit-breaker is still the best answer to our own particular circuit-breaking problems. In this connection I should have welcomed greater stress on the importance of " arc control " in short-circuit interruption, instead of the mere separation of arcing contacts. In reference to recovery voltage, care is necessary to avoid confusion between its amount and its rate of growth, the latter being often a more troublesome factor than the former. It is in this respect that an isolated test plant may be found to stress a circuit breaker more severely than do system conditions. I should like to correct an assertion regarding explosion pots which is made at the bottom of page 291.† The use of an explosion chamber of insulating material applies to certain conditions only, and the steel pot is still retained for many applications. I support the suggestion (page 301) that breaking capacity and voltage should be correlated, and I would advocate going further than the author suggests where high breaking capacity is dealt with. A reason for this is provided on page 303, in that owing to the enormous currents involved at low voltages the stresses set up in forcing a circuit breaker to close on a fault reach impracticable figures, and ordinary closing mechanisms are generally unsuitable. To trip free as soon as contact is made also demands much more robust arcing contacts than are usually provided, in view of the time involved. The most rational solution is the use of as high a voltage as possible for heavy power control. Under the heading " Saving Switchgear " (page 303), the author touches upon distribution economy as exemplified in the American solid distribution network. The case mentioned is that of dense load areas, but the principles employed therein have also been applied a stage higher up—to what are called " secondary " networks—with results calculated to effect remarkable savings. Followed to its logical conclusion, the scheme would do away with distribution substations and their attendant switchgear as we know them to-day, and substitute a standard 5-circuit-breaker switching unit of constant size and breaking capacity for all systems. The effect of such a measure of standardization is difficult to imagine. I believe there are great possibilities for development in the field of remote and automatic control. Some time ago I had to deal with the problem of the totalisator, and the experience gained during its development strongly impressed me with the benefits which might accrue from a closer connection between switchgear and communication engineers, because it is only a short step between communication problems and those of remote control.

Mr. W. Wilson (*communicated*): There are two points to which I should like to refer, namely busbars and protection. The former is given considerable attention on page 295 and in Fig. 28, which shows a special arrangement designed to reduce the heating experienced with closely-spaced a.c. busbars. While there is no doubt that the type illustrated will give much better results than the usual laminated pattern, I am not satisfied that it is the best form. The difficulties attending the design of a.c. busbars are due to the unequal distribution of current in the various parts of the conductor owing to skin or edge effect and proximity effect, and the special difficulty with metal-clad gear is the great increase of proximity effect owing to the necessarily reduced spacing between the conductors of the various phases. So serious have these joint effects become that it is impossible with the ordinary design of busbars to pass a greater current than about 3 000 amperes at spacings of about 1 ft. without an excessive rise of temperature, however many additional laminations are introduced in the usual parallel-strip arrangement.

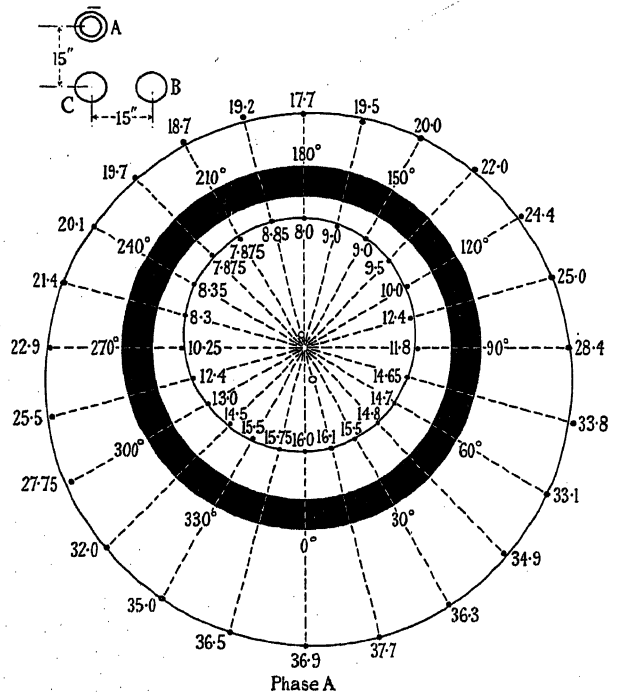


FIG. E.—Relative distribution of 50-cycle alternating current in the uppermost busbar (phase A) of the 3-phase arrangement indicated in the small figure. The current densities on the outer and inner surfaces of the tubular bar employed are shown by the curves.

Although the cross-section of copper is thus increased, the a.c. effects cause the current to crowd to the outlying portions of each phase conductor and also to those nearest the other phase conductors, the remaining portions of the busbar carrying only a small amount of current, and that at a very bad power factor. These effects are illustrated in Figs. E and F, giving the results of tests in which currents of 4 000 and 3 000 amperes respectively at 50 cycles per sec. have been passed through 3-phase conductors. Fig. E shows the distribution of current in the upper one of three copper tubes each having an external diameter of 6½ in. and a thickness of ½ in., arranged as shown in the small sketch. The current density has been measured round both the outside and the inside of the upper busbar at intervals of 15°, and its relative magnitude is represented by ordinates at each point. It is of interest that the heights of the ordinates,

* " Alternating-Current Circuit-Breakers," *Engineering*, 1932, vol. 133, p. 224.
† Since corrected for the *Journal*.

marked by small dots, lie almost exactly on circles. The skin effect is shown by the much greater magnitude of the current at each point outside the conductor than inside; direct measurement shows that the current on the outside surface averages 2·33 times the current on the inside. Proximity effect is indicated by the much greater height of the ordinates towards the other two phase conductors, these being 2·27 times as long as those farthest from them inside the busbar as well as outside. The diagram illustrates graphically the surprising unevenness of current distribution even with such moderate spacings as those shown. The best methods of minimizing the effect are first to give the conductor as symmetrical a shape as possible, and secondly to construct it all in one piece, so that the portions which are producing less heat will receive some by conduction from the hotter portion and so assist in the process of heat

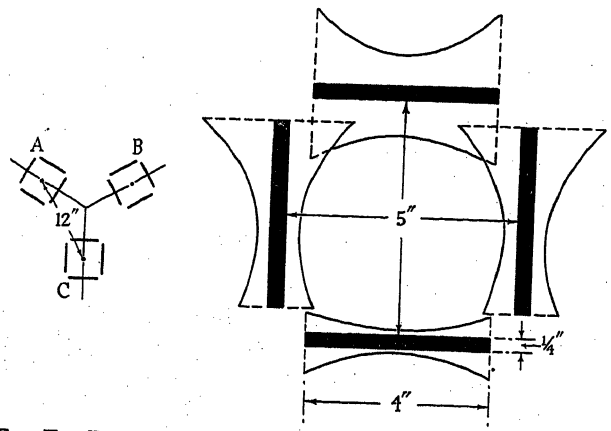


FIG. F.—Relative distribution of 50-cycle alternating current in a 3-phase arrangement of box-type busbars passing 3 000 amperes. The current densities on the outer and inner surfaces of the lowest busbar (phase C) are shown by the curves.

dissipation. Of the various busbar designs, the tubular form is obviously the most symmetrical, while the laminated portion is probably the least satisfactory from the present point of view. The shape shown in Fig. 28, which is almost identical with that illustrated in Fig. F, approximates to the tubular, and at first sight might appear to possess its advantages. The current-distribution curves indicate, however, that this is by no means the case. It will be seen that the distribution does not vary uniformly round the periphery of the "box," as in the case of the tube, but behaves almost as though the busbars were not arranged in a ring, in that the current crowds towards the edges. In this case the current distribution plotted is that of the lowest of the three conductors, and the marked manner in which the current crowds into the top strip of the set and to the upper edges of the vertical strips is well shown. While there is no doubt that this arrangement is much superior to the usual parallel-plate type, since there are no members sandwiched between others and thus rendered almost entirely useless, it suffers from two defects as compared with a tube. The first is that the outside strip, namely the lowest in phase C, is doing very little work at all and might—in this instance, at any rate—be omitted without affecting the efficiency of the conductor very much. Secondly, the conductor is in four separate pieces and thus the heat from the strip at the higher temperature cannot be conducted to the others, which would then serve as additional cooling surfaces. This is the more unfortunate in that the inside strip is the hottest, while the comparatively idle one is that nearest the external atmosphere. As regards protection, British practice has within recent years trended too much in the direction of copying methods produced abroad, and in particular has departed too far from the original principle of instantaneous protection, in favour of foreign methods securing discrimination by means of a time-lag. The full disadvantages of this change have not yet been experienced in this country, since up to the present we have had no large interconnected systems with comparatively long transmission lines between them. These conditions are coming, however, and since the stability of such a system to through faults depends upon the ability of the protective gear to isolate the fault before the two ends of the line have had time to get out of synchronism to the critical extent, it will probably be found that we shall be compelled to return to instantaneous methods before satisfactory working is possible. In this connection I should like to refer to the case of an important transmission line in America* which was originally equipped with the usual type of protection employing a species of time-lag discrimination. During 1928, the first year of working, there were four faults, each of which caused the generators to fall out of step and disconnect the whole station of 250 000-kW capacity. The relays were therefore changed for "high-speed" models, while the inherent time-lag of the circuit breakers was also much reduced by the substitution of an improved pattern. During 1931, the year following these changes, one fault occurred which caused instability, in addition to three others which were cleared satisfactorily; but in order to obviate further trouble balanced parallel-feeder protection was added. This is merely one example of changes that have had to be made within the last 3 years in foreign practice through the use of quite a small time-lag, and it confirms the author's opinion regarding the necessity of rapid action for protective relays. Where pilot-wire protection is possible for feeders, e.g. underground cables, it should always be used, since it combines sensitivity, discrimination, and instantaneous tripping. The difficulty that has arisen within the last few years is that it is impracticable to support pilot wires upon widely spaced towers, and their use is thus attended by great expense. Where it is decided that this expense is not justified, a type of protection should be chosen which depends upon time-lag to the least possible extent, and in this connection the "signal-current" methods described on pages 310 to 313 seem to offer an interesting solution. The carrier-current method appears to be a sound one, and its future seems to be hopeful. The Kapp-Carrothers scheme is of a similar type and should also meet the conditions. The pilot cable employed with this scheme can be used for telephony at the same time as for protective gear without any form of switching, the two functions not

* R. A. HENTZ and J. W. JONES: "Stability Experiences with Conowingo Hydro Plant," *Electrical Engineering*, 1932, vol. 51, p. 95.

interfering with each other in the slightest. The author does not do the McColl system full justice in his reference on page 310. Besides securing stability on the occurrence of through faults by bias opposition on the tripping relay, it is so arranged that the pilot capacitance-current and the other vagabond and harmful currents all pass through the restraining coil of the relay and hence stabilize the scheme, instead of tending to make it trip. Thus, without the tuning arrangement or other added complications of the schemes mentioned later in the paper, this one is quite unaffected by the usual capacitance currents in pilot or feeder, or by high-frequency surges. The author makes but a passing reference to parallel-feeder protection, although he mentions the split-conductor type, which differs in principle from the former only in that both conductors are isolated when one of them breaks down. I should like to ask his opinion as to whether it would not be cheaper in the long run to employ double-circuit lines as a standard and protect them by the parallel-feeder method, on account of the high speed and efficiency of this form of protection.

[The author's reply to this discussion will be found on page 351.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 22ND FEBRUARY, 1932.

Mr. F. C. Winfield: I should like to comment on one or two of the forms of metal-clad switchgear dealt with in Section 2. I consider that Type 1*e* (Fig. 6) and Type 2*e* (Fig. 11) are definitely bad designs. If the term "duplicate busbar" has any real meaning in practice it is surely wrong to lead both busbars directly into a common explosion chamber, which is precisely what these designs do. Types 1*c* and 2*c* suffer from a similar objection in that both busbars may be fouled by a breakdown of the oil insulation in the selector isolator tank, due to moisture or other causes. This is particularly so if these selectors are used for changing-over under load conditions. Type 3*c*, in which two independent selectors are housed in separate tanks, is much superior. The arrangement shown in Fig. 23 seems to be quite sound for the smaller sizes, but at the same time I have always felt that the "replaceable current-transformer" bogy is rather overstressed. In practice replacement occurs quite infrequently in proportion to the total number of equipments installed, and the chief objection is the high charge made by switchgear contractors. A compound-filled current-transformer chamber is better than an oil-filled chamber, and it is a pity to lose the former through overstressing a detail. If switchgear contractors would make special arrangements to deal with replacements of current transformers on a low-cost service basis I think the preference for oil-filled chambers would rapidly disappear. An addition of less than $\frac{1}{4}$ per cent to the cost of all panels would, I think, pay for most of the service necessary in this direction. I am not sure that I agree with the statement (page 299): "It is common practice to put large transformers outside, and the case for similar treatment of well-protected switchgear is equally strong." When the "grid" arrangements were first being considered in this country metal-clad switchgear and cables were for all practical purposes not available, and even now, assuming we could accept them as proven articles, I think that the decision to use mainly outdoor switchgear and lines would be adhered to in view of the very great difference in initial cost. At the same time, to maintain reliable service from outdoor apparatus very careful maintenance will be essential, including conditioning of oil, cleaning of bushings and post insulators, greasing and adjustment of mechanisms, and painting of steelwork, all under difficult service conditions frequently made more difficult by the weather. When reliable information is available in a few years' time as to the cost of maintenance of outdoor 132-kV switchgear, we may find that the disparity in total cost between metal-clad and outdoor switchgear is very much less than would appear at present after taking into account the possible improvement in service. The author's comparison between outdoor circuit-breakers and outdoor transformers is not, I think, quite a fair one. Outdoor transformers are filled with oil and are fitted with conservators and (usually) breathers. The oil and the internal insulation are therefore kept in good condition and require very little maintenance. With circuit breakers, however, a large space exists at the top for condensation of moisture, and this space cannot be eliminated. Bakelized-paper insulation must be used, and this is very susceptible to deterioration due to the presence of moisture. Frequent oil-conditioning, therefore, is essential with outdoor circuit-breakers for high voltages. Apart from this, a circuit breaker is ultimately of much greater importance than a transformer because failure of a circuit breaker may affect the supply in general, whereas failure of the transformer can usually only affect a single supply. For 66-kV and lower-voltage switchgear in the larger sizes I am of the opinion that indoor enclosure ought always to be employed, as it implies a relatively small additional cost, will very considerably reduce maintenance, and, in addition, enables provision to be made (by heating of the switch house) for the prevention of condensation. It also permits of more effective provision for fire-fighting. I have no records of any serious troubles with bakelite insulation where the switchgear is properly housed and kept warm. In this connection I have in mind four similar installations of large metal-clad switchgear all enclosed in buildings, three of which were warmed. A failure of insulation occurred on the unwarmed switchgear, followed by a serious fire. This was almost certainly caused by deterioration of the bakelite due to moisture. Examination of other equipments subsequent to the fire bore out this contention. That particular switch house has since been warmed, and no further troubles have been met with. I agree with the author that it is difficult to find any justification for the difference of permissible temperature-rise in switchgear equipments below the 2 000-ampere rating as compared with equipment above this rating. The fact that B.S.S. 116—1929 gives temperature-rises for oil only, and

makes no reference to insulation, renders this specification misleading. The ratio of 1/125 of the rupturing capacity which the author suggests as a rule for the minimum working voltage of switchgear, seems to me rather better as an indication of the minimum practicable voltage. In new work I would suggest the ratio of 1/75 as a good minimum, the ultimate decision being based on system conditions. If 6-kV switching were adopted for a station having a 300 000-kW output taken by standard 0·25-sq. in. 3-core cables, at least 150 cables and switches would be necessary. Obviously such a number is impracticable. Even if 11 kV were employed nearly 100 such cables would be necessary. The congestion on site and the difficulty of leading away large numbers of cables down adjacent roads is a serious factor in power-station design. The author's remarks about switching capacity are well timed, as it is at present extremely difficult for the buyer to compare designs produced by different manufacturers or to determine the best rating to adopt. The methods of switchgear testing adopted in this and other countries differ so widely and the presentation of results is so varied that it is almost impossible to draw definite comparative conclusions from them, and ultimately the buyer is forced to base his choice on the reputation of a particular manufacturer quite as much as on his own examination of the various designs. The British Standards Institution would be doing very useful work if it would produce some standardized performance tests on the lines the author suggests. He refers on page 308 to the practice of making main generator field-switches operate immediately after the initial movement of the main circuit-breaker. This practice was introduced originally because the older alternators with low armature reaction were incapable of keeping in step when the main field circuit was open, and it was therefore necessary to exclude the possibility of the field switch opening before the main switch. With modern machines this condition no longer holds, and the present practice is to operate the main field-switch and the main oil-switch simultaneously. I do not agree that the short-circuit calculator mentioned on page 315 is the latest addition to control-room equipment, as in America a still later form of calculator has been developed capable of investigating problems of line regulation, current distribution, power factor, and stability in both normal and fault conditions, as well as of making ordinary calculations of short-circuit kVA. I believe that one manufacturer is considering the introduction of such devices into this country. As regards the use of a tandem system of pilots for the control of d.c. traction systems (page 316), I have experience of one suburban system abroad in which this system was employed with rather unfortunate results. It was ultimately abandoned in favour of a radial system.

Mr. L. C. Grant: The application of the metal-clad principle to 66 000-volt switchgear is one of the most important switchgear developments of recent years, and probably the most fundamental change that this e.h.t. switchgear has brought about is the substitution of an oil or semi-fluid dielectric for compound insulation. This change has made possible, amongst other things, the use of an isolating system operating directly on the oil-immersed busbars as shown in Fig. 35, and has resulted in reduced bulk and lower housing costs. In the author's summary of existing switching methods I find no mention of the recently developed oil-insulated cross-jet circuit breaker, which appears to be a development of the explosion-pot circuit breaker. It is probable that the extinguishing action of an explosion pot is most effective at the orifice, and the new cross-jet circuit breaker appears to be an attempt to intensify this effect, although, incidentally the name "cross jet" seems to be a misnomer. Turning to the author's remarks (page 291) about steel contacts, I do not think such contacts are completely reliable as the action of arcing on the contacts produces hard steel globules of glass-like appearance. These globules are not removed by the rubbing action of the switch contacts, and the result is incipient arcing at the closed contacts which quickly develops into contact heating and burning. Is the author definitely of the opinion that the demand upon the circuit breaker is greatest with a low power factor? My experience shows the demand to be the most severe with a power factor of the order of 0·5. Nearer unity the duty is not so heavy, and nearer zero it is on the average lighter, but there appears to be a zone of great variability in which exceptional demands may be made on the circuit breaker.* It is possible that the author's conclusions are based on too few tests to give complete assurance on this point. Short-circuit calculating boards are not entirely above reproach. In the majority of these the results are obtained with direct current on an ohmic board, and it is impossible to eliminate some degree of error. We must be prepared for errors until calculating boards co-ordinating resistance, inductance, and capacitance, come into general use, and until our calculations take into account the change in impedance during the decrement period of a short-circuit.

Mr. D. M. Buist: The paper reveals that switchgear is practically the most costly item in the electrical circuit to-day. Are we not going too far in regard to the strengthening of switchgear? I should be glad of figures comparing the weights per kW of switchgear, transformers, and alternators. The 15 different arrangements of switchgear mentioned on page 288 have been designed to meet conditions many of which are relics of open-type switchgear. The majority of these arrangements would disappear if we had more standardization of conditions, and if less allowance were made for the individual preferences of customers. As regards page 297, I think it is going too far to separate group and section switches by brick cubicles. If this goes on we may expect to see each switch surrounded and separated from its neighbours by 9-in. brick walls, or with moulded reinforced-concrete on top of the metal. This tendency is arising because of the "occurrence of a few fires" (to use the author's own expression). Has he a record of the cause of these fires and of the damage which was done in each case? The additional cost of brickwork, etc., to safeguard against a relatively remote contingency is tantamount to a lack of faith in present-day switchgear. I agree that the practice of placing outdoor-type switchgear

* See *Journal I.E.E.*, 1930, vol. 68, p. 1097.

within a brick building is to be deprecated. According to the paper, in the future switchgear will give a rehearsal of its performance before it allows an operator to switch in. When that day comes there will obviously be no need for operators, because the switchgear will be the " robot " of the electrical circuit. As regards the necessity for earthing resistances (page 307), I expressed myself very strongly on this question at a discussion* in 1925 on a paper by the present author. I cannot understand why engineers are still so exact in their predetermination of the ohmic value of the earthing resistance, which, with the very large power stations now being built, is of small value and therefore very cumbersome. It is placed in a circuit of varying resistance, often having an ohmic value greater than that of the earthing resistance itself, this procedure being based upon the assumption that the only resistance in the circuit between the neutral and the earth plate is what is inserted artificially. The result is that protective-gear calculations are upset, and, to meet varying values of resistance at the earth plate, protective settings would require corresponding adjustments. Has the author ever made any tests to verify this? I have done so, and can assure him that such conditions exist. If a consumer insists upon an earthing resistance, let him bury it in the ground, encased in a metal shield which can constitute the earth plate.

Mr. F. A. Orchard (*communicated*): It would be interesting to know what is considered to be a reliable form of bakelite insulation (see page 290) for semi-tropical conditions. This question is especially important in view of the fact that in the future the market for the larger sizes of switchgear is more likely to be abroad than at home. As most oil-filled apparatus will in the future be for outdoor use, would it not be an advantage if by-pass oil pipes were provided at suitable points which would enable a sufficient quantity of oil to be drawn off for testing purposes at regular intervals without dismantling any of the switchgear? Tests of this kind would be useful for detecting whether moisture had entered the equipment via the mechanical joints. This idea might be further extended to circuit breakers proper, particularly to those types for outdoor use where the examination of the oil is likely to be a fairly lengthy process. If due precautions were taken such draw-off pipes could be arranged for use when a circuit breaker is in commission; this should be an advantage where, under normal conditions, feeders have to remain closed for a considerable length of time. In regard to the proposals for standardized performance tests (page 318), the author rightly bases his interpretation of the severity of service conditions on the circuit breaker's nearness to generating plant; but I suggest that if service conditions are to be entirely simulated it is reasonable to go a stage further and try out the circuit breaker under all its working conditions. It would be interesting to know whether the author proposes that short-circuit tests on outdoor switchgear should be carried out in the open. Does the British test plant to which he refers cater for tests under the conditions met with in actual service, e.g. would an outdoor circuit breaker be subjected to short-circuit in the open under both fair and severe weather conditions? The risk of widespread damage may have led to the decision to enclose almost completely the apparatus under test, as in the test plant already referred to, but such an arrangement rather improves the service conditions which the performance test proposes to imitate. I feel that pressure and short-circuit tests should be carried out simultaneously, and, further, short-circuit tests should be made with normal pressure applied under the worst possible weather conditions likely to be experienced where the circuit breaker has to be finally installed.

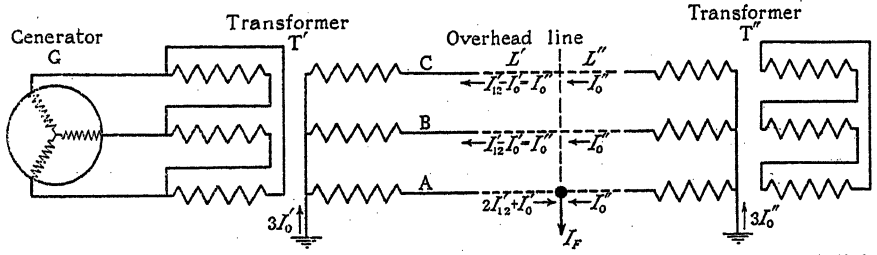


FIG. G.—Distribution of fault currents in 3-phase transmission line connected to solidly earthed star/delta transformers.

Mr. G. G. Smail (*communicated*): I am interested in the dual-circuit short-circuit calculator mentioned by the author and illustrated in the paper. The object of this is to evaluate the probable short-circuit kVA which the switchgear installed on the grid will have to rupture, and to determine the values of short-circuit currents available for relay operation. On overhead-line systems earth faults are more probable than phase faults. An earth fault constitutes an unbalanced load on the system and the ordinary method of calculating 3-phase short-circuits is not applicable. The reactance of the network is different under earth-fault conditions, and the paths by which current is fed to the fault depend on the transformer connections. In the case of the grid, the transformers are all star-connected, earthed on the h.t. side, and delta-connected on the l.t. side. Under these conditions fault current can flow from all the transformer neutrals. Transformers which have no generating plant behind them are energized via the two sound phases. Fig. G shows the simple typical circuit consisting of a line connecting two transformers, one of which has generating plant behind it. Phase A is assumed to be earthed as shown. In the calculation of earth-fault currents one may use the method of symmetrical components due to Mr. C. L. Fortescue and applied particularly to the consideration of earth

* *Journal I.E.E.*, 1925, vol. 63, p. 1028.

faults by Mr. A. P. Mackerras.* The application of this method to the circuit of Fig. G is shown in Fig. H. The fault-current distribution at any point is derived from the determination of the three symmetrical components known as the positive, negative, and zero phase-sequence components. Typical vector systems are shown on the right of Fig. H. I'_{1A}, I'_{1B}, and I'_{1C} are three symmetrical vectors having positive phase sequence, I'_{2A}, I'_{2B}, and I'_{2C} have negative phase sequence, and I'_{0A}, I'_{0B}, and I'_{0C} have zero phase sequence. These circulate between the fault position and the transformer neutrals. The zero phase-sequence reactance of the grid lines has been calculated to be 1·57 ohms per mile. In Fig. G, T′ and L′ refer to the transformer and line on the left-hand side of the fault. T″ and L″ similarly refer to the right-hand side of the fault. In the equivalent network of Fig. H the same symbols refer to their reactances. The suffixes 1, 2, and 0 relate to the positive, negative, and zero phase-sequence components, and A, B, and C to the phases. Referring to Fig. H,

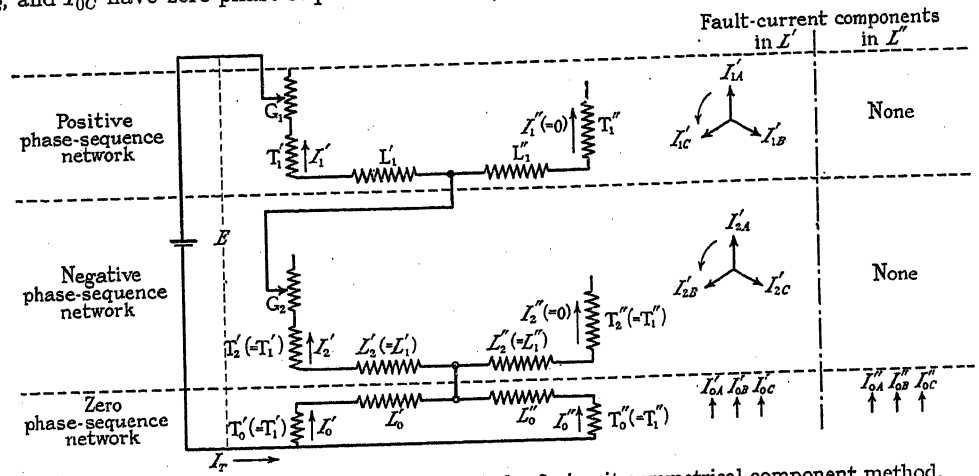


FIG. H.—Calculation of earth fault currents by 3-circuit symmetrical component method.

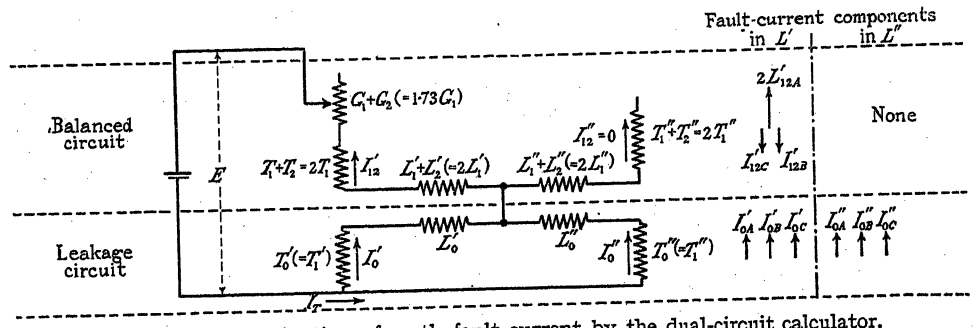


FIG. J.—Determination of earth fault current by the dual-circuit calculator.

components must be determined separately. The total earth-fault current has been shown to be $3E/X_1+X_2+X_0$, where E is the voltage to neutral and X_1, X_2, and X_0 are the total equivalent reactances of the network to the positive, negative, and zero phase-sequence currents. The components are all equal at the fault. Since the positive and negative phase-sequence networks are practically identical, these two components are very approximately equal to each other at all other points. The positive and negative phase-sequence components flow in the same paths which would be traversed by the currents feeding a 3-phase short-circuit at the same point. The reactance offered by the system to each of these components is identical to that offered to balanced 3-phase currents, with the exception of the negative phase-sequence reactance of the generating plant, which is 73 per cent of its normal positive phase-sequence reactance. The zero phase-sequence components are confined to the h.t. lines, and the fault current and its distribution would be found as follows:—

The total earth-fault current I_F	$= 3I_T = 3(I'_0 + I''_0)$
Fault current in Phase A fed from left	$= I'_1 + I'_2 + I'_0$ $= 2I'_1 + I'_0$
Fault current in Phase A fed from right	$= I_1' + I_2'' + I_0' = I_0''$
Current in phases B and C	$= -(0{\cdot}5I'_1 + 0{\cdot}5I'_2)$ $+ I'_0 = I''_0$ $= I'_0 - I'_1$
Current in neutral of transformer T′	$= 3I'_0$
Current in neutral of transformer T″	$= 3I''_0$

In the dual short-circuit calculator the above method has been simplified for the purposes of a calculating table so that only two components are necessary. The

* See also C. G. CARROTHERS: *Electrical Review*, 1929, vol. 105, p. 309.

arrangement for the case given in Fig. G is shown in Fig. J. The positive and negative phase-sequence networks are replaced by a single network in which the reactances of the lines and transformers are twice the normal 3-phase reactance, and the generating reactances are 1·73 times the normal short-circuit reactance. This combined network is called the " balanced component circuit." The second circuit is known as the " leakage component circuit " and is identical with the zero phase-sequence network previously mentioned. The balanced current components consist of the sums of the positive and negative phase-sequence components, and are shown on the right of Fig. J. In using the calculator the instruments are suitably scaled so that the fault-current components are read direct without the use of conversion factors. The total fault current and its distribution in the network are determined from the readings of the balanced and leakage component ammeters I_{12} and I_0 respectively.

The total earth-fault current $I_F = 3I_T = 3(I'_0 + I''_0)$

Fault current in phase A fed from left $= 2I'_{12} + I'_0$

Fault current in phase A fed from right $= 2I''_{12} + I''_0 \ (= I''_0)$

Current in phases B and C $= -I'_{12} + I'_0 = -I''_{12} + I''_0 (= I''_0)$

Current in neutral of transformer T′ $= 3I'_0$

Current in neutral of transformer T″ $= 3I''_0$

The generators are shown as variable rheostats. This enables the various running conditions to be taken into account. It is also possible to use the " balanced " circuit by itself to investigate 3-phase faults. The only necessary alteration to the circuit is to alter the generator rheostats to the value corresponding to the balanced reactance. Absolute accuracy is impossible with any type of calculator, because certain factors are present which it is impossible to take into account in a calculator circuit. An indeterminate variable is the arc and earth-plate resistances. Another variable is the short-circuit decrement which becomes of importance when relays, having a time-lag, are used. This can be most satisfactorily allowed for by referring to typical decrement curves by which the current value at any instant after short-circuit can be obtained. When the network consists entirely of overhead lines the resistance of the lines may be neglected. The maximum error introduced by this would be less than 5 per cent where the ratio of line reactance to line resistance is about 3. Where problems such as transient voltages and high-frequency phenomena require investigation, model circuits containing capacitance, inductance, and resistance must be used. Such a calculator would be large and expensive, and should preferably be built up so that any system could be represented by rearranging the components suitably. Where the object of the calculator is to determine short-circuit currents, a resistance calculator of the d.c. type is sufficiently accurate and is preferable to the a.c. calculator on account of its simplicity.

[The author's reply to this discussion will be found on page 351.]

North-Western Centre, at Manchester, 23rd February, 1932.

Mr. S. Ferguson: I do not agree with the author regarding the reliability of British circuit breakers, as the rupturing tests which we have carried out lead us to believe that a large proportion of the circuit breakers at present in service have nothing like so large a rating as was originally assigned to them. Faults such as " slowing up " and " stopping and reclosing " would actually take place on some of the designs at present on the market, if the appropriate tests were conducted. With regard to the author's standard conditions for rupture tests, while I agree that these are necessary I would point out that they are very fine points in comparison with the general question of knowing that the circuit breakers will actually rupture the powers for which they are designed. What factor of safety would the author suggest for rupturing ability?

Mr. T. T. Evans: In his comparison (page 291) between horizontal and vertical switchgear the author intimates that there is a limiting voltage up to which air insulation can be employed at the isolating points, and I should like to know what he considers that limit should be. In my opinion 33 000 volts is the limit to which air insulation can be employed with safety, because of the dirty and damp nature of our atmosphere and the fact that for higher voltages the space required would be rather large. Complete oil insulation should therefore be provided for voltages above 33 000 volts, even at the points of isolation. In all the cases referred to in the paper, complete oil insulation entails first isolation, then in some cases the draining of oil, and finally the removal of the circuit breaker for inspection and maintenance. This would appear to be a long and costly procedure, particularly at a time when speed is essential. The author omits to mention an important class of switchgear, distinguished by its method of isolation, namely the vertical lift-up type. For voltages where complete oil insulation is necessary, particularly at the isolating point, this class of switchgear offers many advantages. Figs. K and L (pages 348 and 349) show a duplicate busbar 2-switch scheme, Fig. K being in diagrammatic form. The chief advantages of vertical lift-up switchgear are: (*a*) Complete oil immersion of all bare live connections, even with the circuit breaker in the isolated position. (*b*) The oil circuit-breaker in the service position is fixed in a solid and rigid manner. (*c*) The busbars are arranged in a convenient and safe position in relation to the oil circuit-breaker, and if desired a complete floor can be arranged between them. This reduces fire risk to a minimum. (*d*) Complete phase separation by earthed metal is provided.

Mr. W. Kidd: Where space is limited the drop-down type of switchgear is usually more convenient than the horizontal draw-out type, although both types give satisfactory service. A change-over from one set of bus-

bars to the other can be made rapidly on drop-down gear. With regard to Fig. 37, the author suggests that considerations of temperature-rise render necessary a special type of busbar for currents of 3 000 amperes; I should be glad if he would give some further information about these special busbars. He also states that the ratio between voltage and kVA breaking capacity should be 1 : 125, and that for large power stations the economic switching voltage is about 12 000 volts. In my opinion the voltage should be substantially obsolete in a few years' time. Control boards are at present far too big; the ideal board for a power station would be of the supervisory type with an illuminated diagram which would differentiate between live and dead circuits. Miniature indicating instruments would be incorporated in the diagram, and small telephone-type control switches would be employed. The idea of trying to visualize the total load from the positions of the pointers on numerous instruments should be abandoned in favour of the use of summation instruments. The

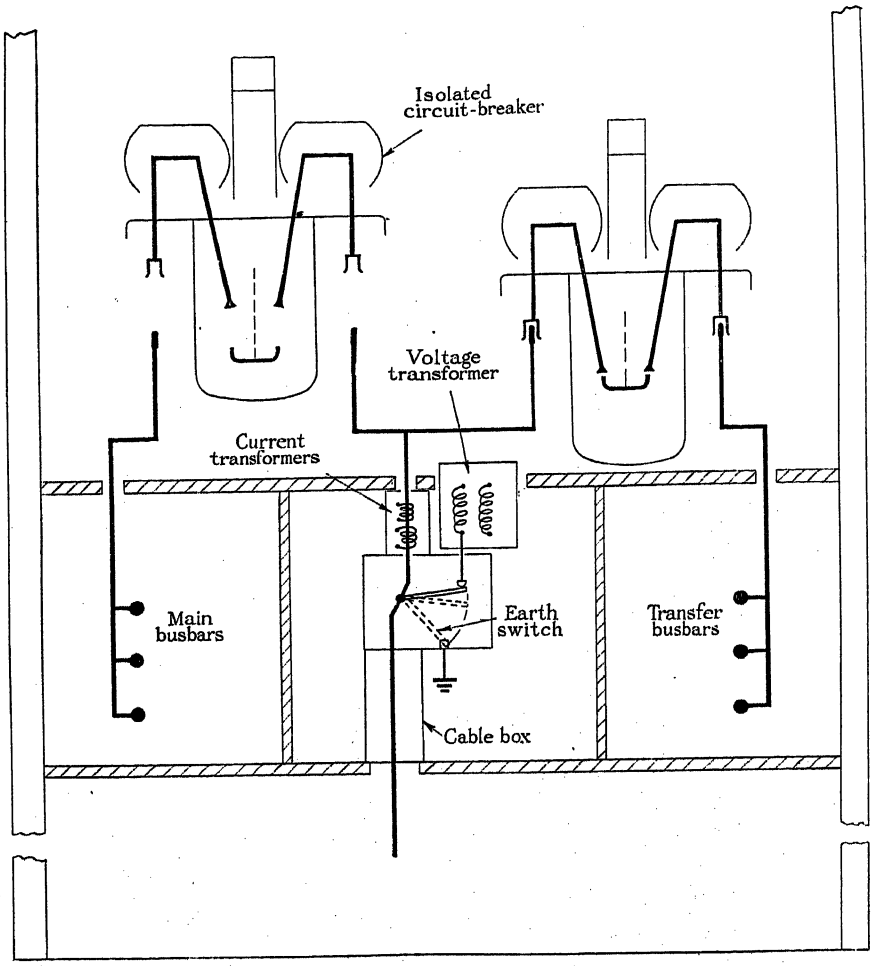


FIG. K.

higher, and as regards future large stations connected directly to the "grid," a good case can be made out for switching at 132 kV. Would the author seriously advocate 12-kV switchgear when the short-circuit kVA was of the order of 1½ million? Single-switch substations, mentioned on page 303, were adopted in Manchester before the War, and at the present time there are about 200 of them in operation. Each substation has two high-voltage feeders and one, two, or three, transformers rated up to 3 000 kVA, but only one circuit breaker; the supply can be maintained even when the circuit breaker is made dead (see Fig. M, page 350). In regard to control boards, even the type foreshadowed by the author will probably be relays should be placed in the switch house, or in a small room immediately adjacent to the switch house, so as to render it unnecessary to bring the present type of multi-core cables from the switchgear to the control board. What should be brought in is the smaller telephone type of multi-core cable, and if this were done a large saving in the cost of cable work and buildings would result. Further, the operator would have his control board within a reasonable range of vision and reach. The operations of switching and control should be kept distinct, and the operator's control board should have an entirely separate diagram. The control engineer should give definite instructions to the operating engineer. I agree with the author that metal-clad switchgear will

probably be adopted more in the future than it has been in the past, but I think that if possible a housing should be provided for it, because if compound-filled switchgear is exposed to the sun, local expansion of the compound occurs. Expansion chambers do not relieve the trouble, which causes leakage and, if the switchgear is small and incorporates thin castings, may give rise to fractures.

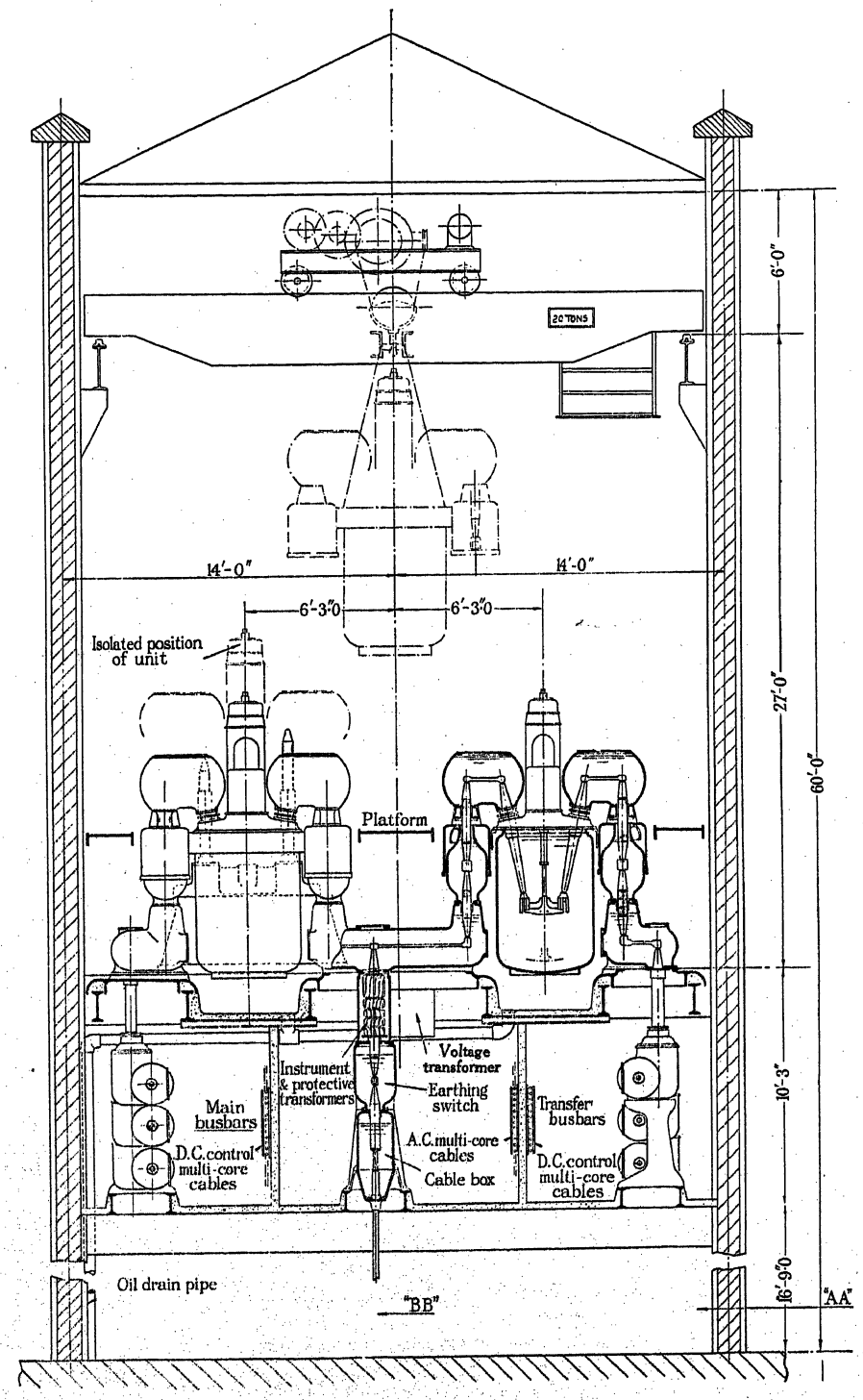


FIG. L.

Mr. H. Pearce: I shall refer particularly to Appendix I, as I feel that the author's standard short-circuit tests for oil circuit-breakers form one of the most important parts

of the paper. While I agree that standardization is a splendid thing when carefully applied, it is essential that it should avoid imposing unnecessary limitations on design or practice. As an instance of a difficulty that the author has himself experienced in this connection, it may be noted that he gives the results of several tests, not one of which complies with his own standard conditions, since the tests were made at 40 cycles per sec. The criterions of severity of the test are still very little understood. The author himself, as Mr. Ferguson mentioned, has left out what is believed by many people to be the most important factor, viz. the rate of rise of recovery voltage. Assuming that the power factor of the short-circuit current is fairly low (of the order of 0·1, as mentioned in B.S.S. No. 116—1929), at the moment of break the voltage is very nearly at its maximum value. The way in which the voltage will rise to the maximum depends entirely on the constants of the circuit on the generating-station side of the circuit breaker. The reactance, which dictates principally the drop in voltage, will, with any capacitance there may be between that reactance and the circuit breaker, form an

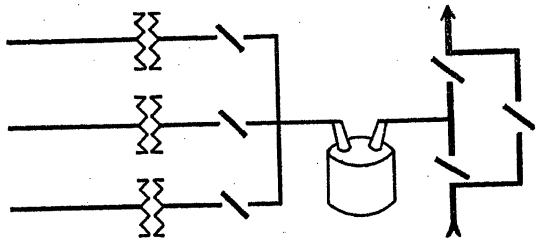


FIG. M.—Manchester single-switch substation.

oscillatory circuit. The frequency of that circuit and the magnitude of the recovery voltage will together largely determine the rate of rise of voltage, though other and smaller oscillations may also be present. The author carefully adjusts the power factor of his test circuit to the specific value 0·1 mentioned in B.S.S. No. 116, a procedure which makes the duty of the circuit breaker easier because it reduces the rate of rise of voltage. I cannot believe that B.S.S. No. 116 is designed to make the duty of the circuit breaker lighter when it is under test. I hope that as short-circuit testing becomes more common and more precise we shall find some way of defining the severity of the test. At present the only device for measuring the rate of rise of recovery voltage is the cathode-ray oscillograph, which is still a rather cumbersome piece of laboratory equipment, unsuitable for regular use on short-circuit tests.

Mr. W. A. Coates: I propose to confine my remarks to those portions of the paper which deal with 132-kV apparatus. While no engineer would question the reduced insulator-maintenance and site costs associated with metal-clad equipments, against these advantages there must be set off a measure of inflexibility, and often of inaccessibility, which might well tip the scales in favour of open-type 132-kV switchgear of equal initial cost. Designs are at present being prepared for extensions to two of the " grid " stations in Scotland. These, which are of the 3-switch type (see Fig. 39), must now be altered to what is termed the " mesh " connection, to bring in an extra feeder. Equipments rather like that shown in Fig. 35 could clearly be assembled to form a 3-switch group, but I cannot imagine such a modification to a 5-switch mesh system being carried out, except by shutting down the whole station for some weeks. With the standard open-type equipment, I expect to carry out the above extensions without once interrupting the supply. Further, practically no changes will be needed to existing structures or foundations, and all the present items of equipment will be used again. It would be difficult to design a metal-clad switchgear system to which the extensions mentioned could be effected without scrapping a lot of existing material, and I should like to know whether the author has a solution for this problem. The footnote to Fig. 34, explaining the functions of the by-pass isolator A, is more plausible than complete. The switches at A are intended to permit access to the feeder circuit-breakers for maintenance purposes. By closing the by-pass, the busbar coupler on the right can be used in linking up to the top set of busbars. Even with a metal-clad design, therefore, a by-pass isolator should be included, to give maintenance and operating facilities equivalent to those of open-type switchgear. The ingenious principle involved in the isolating feature shown in Fig. 35 strongly resembles the patented arrangement of bushings which is being employed on the grid circuit-breakers in this district, as well as in East Anglia and South Wales, with the object of speeding-up erection and maintenance work. Were the bushings shown in Fig. 35 actually designed for 132 kV, and, if so, what is their overall diameter? The extra length of earth band provided will be useful for the accommodation of current transformers, which in this design must all be on one side of the circuit breakers. The busbar side bushings, being allocated one to each busbar, are obviously not usable. The problem of including the circuit breaker in the relay protective zone is rather difficult with this arrangement, and I should be glad to know its correct solution. The condenser-coupler method of potential measurement seems to be the result of a firm determination not to do the obvious. The weakness to which high-voltage potential transformers were at one time subject have been eliminated by modern coil-winding machinery, and the most recent designs, such as are being used on sections of the grid for which my firm is responsible, incorporate features of coil-shaping and shielding which make the winding quite surge-proof. No primary fuses are used, as they are deemed quite unnecessary. A straightforward device of this type, costing no more than a capacitance coupler and needing no adjustment with varying burdens, is surely preferable to the mysterious assembly of tuning devices shown in Fig. 36.

Mr. E. C. McKinnon: The title of the paper implies that the small paragraph devoted to tripping batteries completely covers all the developments during the last 7 years in relation to storage batteries for remote control, although this, of course, is by no means the case. I agree with the author regarding the deficiencies of Leclanché cells, and I fail to understand the attitude of Post Office engineers in adhering to this type of battery for telephone systems when suitable secondary batteries of various makes are readily available. With regard to

the relative advantages of the nickel-iron and lead-acid secondary batteries, I would point out that the nickel-iron type of alkaline battery is the one secondary battery which cannot be trickle-charged. The author is by no means alone in his failure to differentiate between the nickel-iron and nickel-cadmium types of alkaline batteries.* Lead-acid batteries have many points of advantage, particularly the types specially designed for substation work, and their use is rapidly extending.

Mr. T. W. Ross: I will confine my remarks to the section dealing with protective gear of the distance type. The distance relay had been used abroad for some years prior to the commencement of work on the British grid, and when it was found necessary, in protecting the 132-kV lines, to depart from the well-established practice of using pilot wires, this alternative was the first choice. At that time the large majority of distance relays were based on the impedance-measuring principle, and when carefully designed they had proved entirely satisfactory. Impedance relays of a type which had been designed and manufactured in this country for export were chosen for the protection of the first section of the grid. Their 2 years' service in Scotland has demonstrated that this choice was fully justified: the relays have operated and discriminated correctly on the faults which have hitherto occurred, in spite of the statements on page 310 and in Appendix III to the effect that the resistance of the arc might lead to incorrect location of the fault by impedance-measuring relays. Turning to the author's experiment for settling the rival claims of reactance-measuring and impedance-measuring relays as regards fault location, the method of carrying out this experiment must give results favourable to the reactance relay, since the arc obtained is not entirely comparable with that resulting from a fault under practical conditions. The great majority of line faults result in a flash-over on an insulator or string of insulators, which on 132-kV lines means an arcing distance of the order of 40 inches. The electrodes in the experiment were spaced 72 inches apart, and, moreover, the arc was struck in space and not across the face of an insulator. This latter point is of some importance, since the arc resulting from the flash-over of an insulator usually clings to the insulator surface and does not spread as rapidly as an arc in space. The difference in the test conditions may explain the comparatively high values of arc resistance indicated by the experiment. Reference to the available data on the subject shows that the figures given in the paper are from 30 to 60 per cent higher than those resulting from other experiments carried out for the same purpose. It would be of interest to know how the R.M.S. values shown in Appendix III were deduced from the oscillograms, since the current and voltage wave-forms must have been considerably distorted. This distortion would cause the apparent power factor of the arc to be less than unity, with the result that distance relays might be appreciably affected unless special precautions were taken in their design. The distance relays of the impedance type in use on the British grid are designed for quick operation over 70 per cent of the feeder length, and having once operated they do not reset until the impedance has increased to more than twice that of the whole feeder. It is therefore apparent that the arc has not time to lengthen before the relay has taken up its position. This it will do in less than 0·1 sec. A time-delay has, of course, to be introduced for faults on the remaining 30 per cent of the feeder length. The time-delay may be of the order of 0·7 sec. without the addition of any extra impedance due to the arc, and if we assume an arc of reasonable length the time-delay may automatically be increased to a maximum of 1 sec. Is it, therefore, desirable, in order to eliminate the probable extra time-delay for faults on 30 per cent of the feeder length, to substitute all the complications of reactance-measuring equipment for the comparatively simple impedance relay? Simplicity, in my opinion, is of greater importance than any theoretical advantages, and simple relays are more likely to be satisfactory in service than the many complicated relays used in the author's distance-measuring equipment.

Mr. S. R. Mellonie (*communicated*): The relationship suggested on page 301 between the kVA rupturing capacity of the switch and the minimum voltage gives a figure of 320 volts for a rupturing capacity of 40 000 kVA, and the author will agree that the cost per kVA of such a unit would be high. A more satisfactory figure would be twice the voltage. I should welcome the author's opinion regarding the maintenance of metal-clad units. As the only exposed insulation adjacent to live metal is that in the spouts, the question arises whether this can safely be cleaned when the busbars are alive. With a specially-designed circular hollow cleaner made of insulating material, which makes it unnecessary for a man to place his hand any nearer the live metal than the outside earthed cover, the risk appears to be very small. In industrial districts the amount of dust which collects in the spout insulators is considerable, and if this could be removed without making the busbars dead the advantages of metal-clad switchgear would be still greater than at present.

* The reference in the advance copies of the paper to the nickel-iron battery has been altered for the *Journal*.

The Author's Reply to the Discussions at London, Newcastle, and Manchester.

Mr. H. W. Clothier (*in reply*): The discussion is lengthy, but it may be hoped that it has clarified some of the many outstanding problems. It has turned mainly on the rating and test-performance of circuit breakers. It has raised a repeated demand for a specification of the rate of rise of restriking voltage, the reply to which is that the paper covers the point by specifying the constants of a standard test-circuit upon which all ratings shall be based. Criticisms of the proposed standard test-circuit conditions are such as will, I think, lead in the end to a much better understanding on the part of the purchaser of how to determine circuit-breaker ratings for different vicinities on his system.

The erstwhile demand for radical changes in breaking-capacity methods has sobered down to suggestions of boxed improvements in the arcing contacts of oil circuit-

breakers. I agree that increased margins are within reach by these means, but further investigation is necessary, particularly in respect of " making " on short-circuit, before the limits of the improvement can be determined. The proposals of the paper for increasing the range of voltage for which metal-clad construction is advantageous have not been shaken.

Absolute reliance on continuity of supply is of such vital public importance that I have been led to suggest that the operation of protective systems should come more closely under the observation of the Institution.

An extraordinary number of important questions and points of detail have been raised in the discussion, which spread over six evenings, and an endeavour is made below to reply to them collectively under analysing headings, as far as possible in the order of the items in the Table of Contents printed on page 285.

Switchgear Construction.

Innovations.

I do not agree with Mr. Coates in associating his Fig. A with the German design, which, on reference to British Patent No. 23348/1913, is found to be as shown in Fig. N. Rather his outline is a replica

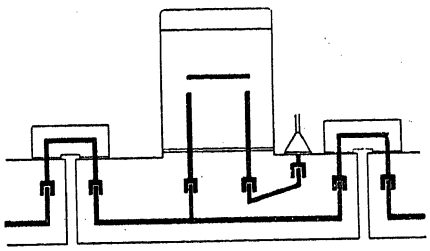


Fig. N.—Oil isolation with ring busbar.

of an illustration that I have already recorded in the *Journal*.* Moreover, he is only right in assuming that his arrangement of condenser-insulated busbars differs from what has hitherto been seen in respect of the questionable advantage of the absence of oil-filling. Figs. 17 and 21 of the paper show busbar tubes so small that the busbars could only be insulated by completely covering them with insulating material, which was also of bakelite paper with condenser-layers of foil.† The only difference is that the small remaining clearances were filled up with oil to avoid any risk of ill-effects from possible air-spaces.

I agree with Mr. Evans as to the limit of 33 000 volts for air-insulation of isolating orifices, and for power-station services on the lines of Fig. 15 oil is preferable at 33 000 volts and under. As Mr. Evans says, the vertical lift-up has been omitted from the list of generic classifications (page 288). This was due to my not having, at the time of writing the paper, the information now shown in Mr. Coates's Fig. A and Mr. Evans's Figs. K and L, and to the abandonment of my own earlier proposals for this class.

Contrary to Mr. Evans's statement, the ordinary inspection and maintenance of circuit breakers of the new forms with complete oil-insulation shown in the paper only necessitate the usual process of removing the tank in the suspended types, or the draining of oil for access through a manhole cover in the type with the tank resting on the ground. This is done, after isolating and earthing, by means of hand levers, which is really not such a long and costly procedure as in the form he advocates, for which the circuit breaker, complete with its tank, must be removed by a crane, as shown in Mr. Coates's Fig. A, before the tank can be removed. All Mr. Evans's itemized advantages (*a*) to (*d*) apply equally to Figs. 21 and 35, except for the possible addition of a floor, which is not switchgear and seems to be losing one of the advantages of metal-clad switchgear, namely self-contained unit construction and factory grouping; and in my preference for busbars above circuit breakers of this particular type I have Mr. Ferguson on my side.

Instrument Transformers and Instruments.

I heartily endorse Mr. Winfield's preference for compound-filled current transformers in small and medium-sized switchgear. No one outside the factory could realize the additional cost and delay that come in the train of accessible current transformers and oil-filling in the truly compound-filled class of switchgear. The extra cost would assuredly be paid over and over again if on the few necessary occasions the compound-filled chambers were brought back to the works, notwithstanding the need for breaking and remaking the cable joint. Mr. Moore suggests that the ratio of meter transformers should be checked every 10 years, to ascertain whether there has been any ageing, with consequent change of accuracy in the readings of instruments. He raises a doubt, but gives no evidence of ageing of either current transformers or voltage transformers. Thousands of the former have been fixed solidly in compound-filled chambers for use during the last 25 years, and voltage transformers have always been removable.

In further reply to Mr. Moore, I think that other papers recently read before the Meter and Instrument Section have recorded details of progress in instruments so adequately that there is no need for repetition here. I agree on the importance of accuracy in integrating-meters, in view of its effect upon revenue. The meter, unlike the transformer, contains moving parts, which may be slowed down by age, and must be periodically checked.

I do not like to hear about direct access to primary fuses or power-transformer terminals. It savours too much of the risk of accidental access to live conductors. Rather than eliminate plug connections, I would concentrate upon perfecting their good-contact-making quality, for the sake of easy withdrawal of apparatus for safe isolation. Mr. Moore says that much expense and delay would be avoided if all primary and secondary fuses were made accessible. This may be thought to be so in considering the operator's time only; but accessibility of high-voltage apparatus must not be attended with personal risks, and for this reason some high-voltage fuses have been deliberately so placed that they cannot be reached until the circuit breakers connecting them to the busbars have been opened and isolated. As to the secondary side, although I agree

* *Journal I.E.E.*, 1925, vol. 63, p. 428, Fig. 5; also British Patent No. 110808/1916; and Figs. 8 and 9 of my British Association paper, 1927.

† British Patent No. 339677: Application date 13th September 1929.

with the need for easy access when considering the comfort and efficiency of the operator, another vital point, mentioned elsewhere in another connection, is that some protection is also necessary as nearly adjacent to the secondary winding as possible. This is because a short-circuit on the secondary generally means a burn-out of the primary, and so the protection is required to cover the whole of the circuit, and not only the part from where a conveniently accessible fuse would be placed.

The truck type, in which the whole of the instruments, the wiring, and the current transformers and voltage transformers, are removable intact, may be thought to be ideal for meter testing; but ought Mr. Moore to couple it with the cubicle type, in which the tester has to work in a confined space, which may be alive inadvertently? Moreover, even with the truck type, if the whole thing is withdrawn, great care must be taken before making full use of the facility, since otherwise it is possible to get high voltage on the bare exposed conductors through the voltage transformer. Again, it is neither safe nor convenient to make a test by passing high voltage through the panel; and so all that is really gained is that the current transformer is made accessible.

Tests, other than for ordinary accuracy of transformers, connections, and meters, such as a "thorough test of metering equipment" before leaving the works and on erection, are usually controlled by the purchaser's specification. Frequent repetition may involve costs that the purchaser is not prepared to face. It depends upon what is meant by "thorough."

Horizontal or Vertical.

From illustrations of broken top-plates shown by Mr. Ferguson on the screen at Manchester and by Mr. Wilkinson at London, one would fear distortion of busbars when placed immediately over these top-plates. Mr. Ferguson assures us, however, that in thousands of tests this has never occurred; but the horizontal type has been proved equally under tests. I think that the evidence is, if anything, in favour of the horizontal type, in which the circuit breakers are more remote from the busbars; but really in both types it is a matter of forethought in design, and there must always be adequate provision for holding down the circuit breaker. The same applies to top-plate insulators, which, if insecurely fixed, may be forced into the busbar chamber structure in the vertical type; but incidents of this kind may be common to either class, and although such an occurrence would be less harmful in the removable horizontal type, because it would be easier to repair on the circuit breaker, in both forms it is only a matter of knowing what stresses are to be met with, and designing accordingly.

Mr. Wilkinson draws attention to a point already dealt with in the paper (page 291), namely that the horizontal arrangement is designed in accordance with the usual British practice of using change-over switches in preference to a duplicate circuit-breaker for changing over from one busbar to the other; but I do not agree with him that it does not give the same scope or range of operation. I have always contended that, for the same cost of production, one circuit breaker is better than two, because there are fewer parts, and these are of a higher quality, and are therefore less costly to maintain. There is not much to be gained by the wide separation of compound-filled busbar chambers; this is an idea associated with open-type switchgear, but not relevant when busbars are properly metal-clad.

I agree with Mr. Kidd that both the horizontal and the vertical type will give satisfactory service, provided they are designed with the same care and with equal study of the varying characteristics of each; but I do not agree that a change-over can be made more rapidly with the vertical type. This also is a matter that can only be judged from the method adopted.

Disposition of Busbars and Phase Separation.

Although I agree with Mr. Winfield on the desirability of avoiding having two sets of busbars and connections thereto in the same chamber, it must be admitted that there are very few ways of doing it. Fig. 15 is satisfactory, but is not immune from the criticism, because when one isolating switch is closed it connects its busbar into the other tank. Duplicate circuit-breakers (Figs. 5 and 10) are not immune, because, when both circuit breakers are in position, and one is closed, the idle busbar connections and the live busbar connections both enter the idle circuit breaker. Fig. 8 does it; but this necessitates complete removal of the circuit breaker when changing over. Fig. 35 is near perfection, because the unused busbar connection is both isolated in two places and also earthed in two places, one of which is visible. At the same time it should be recorded that, although the largest proportion of duplicate busbar switchgears do not comply with the ideal, I do not know of any failure in consequence. No device that has to change over on load can comply, because there must obviously be one last contact that has to be closed in order to join the two busbars together; but it is possible so to interlock that this last contact shall not be made until the busbars are paralleled. Again, at the place where the busbars are paralleled the two must come together in one chamber, and before paralleling the potential difference still obtrudes itself.

Mr. Blandford asks whether it is desirable to obtain complete phase-separation in the smallest types, rather than to use tanks with an air space common to all phases. This seems to me to be merely a question of cost of production. Comparing the two alternatives, I think that the combined quality of three separate enclosures has to be greater, and is therefore more costly, than that of a single enclosure of the same switching capacity. Up to and including 750 000 kVA, I prefer the common tank with earthed metal between phases; but I would not attempt to fit complete barriers, either of metal or of insulating material, between phases in one tank, on account of the tendency to distortion of the barriers by occasional greater stress in one phase than in its neighbour. Beyond 750 000 kVA, other mechanical considerations are a determining factor and lead to a single tank for each phase. Mr. Coates also refers to testing circuit breakers with single versus three tanks, and I agree that common top-plates and air spaces introduce a distinction in respect of test requirements. It may be argued, however, that it is not sufficient to test separately one single-phase unit of a

3-phase circuit breaker, or, if this is done, it is not correct to assume that the proved breaking capacity of one unit can be multiplied by three to give the rating of the 3-phase circuit breaker, since under actual service conditions any one phase may do more work than either of the other two phases. If it is assumed to do 50 per cent more, it may be taken as a guide that the sum of the kVA-performance values of the three units tested individually is of the order of 30 per cent greater than the corresponding value for the three units taken collectively.

For voltages of 66 000 and upwards, it may be very difficult to obtain 3-phase testing on test-plants, owing to the large size of the transformers required; and, seeing that circuit breakers for such voltages are always earthed in service, Appendix I (page 319) allows for the alternative of testing single-phase units.

Switchgear Lay-out.

Mr. Wedmore raises an issue about duplicate busbars, and in reply I should like to refer him to the 1925 paper and discussion,* in which he will see that my criticisms were not directed against duplicate busbars as such, but rather against duplicate circuit breakers when used with duplicate busbars. I contended then, as I do now, that duplicate busbars have certain uses in large generating stations, but that one of these is not for the kind of rapid change-over that warrants the use of duplicate circuit breakers also. It is preferable to isolate the circuit first, and then to make the necessary change-over. Mr. Wedmore speaks of his conversion by the experience of the last 14 years as though it was only in that period that development in a "sufficiently reliable form" had taken place; but the development has been satisfactory over the last 25 years at least. Switchgear units of the largest capacity still in use to-day had already been made more than 14 years ago, and these units were fitted with duplicate busbars and single circuit-breakers, as was all other power-station metal-clad switchgear prior to that time. My experience with this type of switchgear has not justified Mr. Wedmore's suggestion to place a wall between duplicate metal-clad busbars, and I think he is mistaken in saying that the additional cost would be very small. In some cases, indeed, such as those of Figs. 21 and 35, it would lead to an entire re-design of the switchgear, and for what seems to me little or no gain he would have to abandon the factors leading to the very economy that he in common with other speakers demands. I feel that the hankering after duplicate circuit-breakers changing over on load, and separation of duplicate busbars by walls, has been handed down from the time when the control of operating conditions was very different from what it is to-day.

Mr. Highfield finds minor mechanical faults too frequent, and calls for greater attention to the mechanical movement. He suggests compressed-air or hydraulic operation. Mr. Trencham gives the cue for saying that, as electrical engineers, we need no excuse for taking advantage of the "wonderful flexibility" of the power we control; and so we do not disregard our own product for power-supply purposes in operating switch-mechanism. But I think that, even apart from this, the greater cost of producing and maintaining a power supply by pneumatic or hydraulic systems must be a reason for their non-adoption. Mr. Highfield instances railway signalling by compressed air, but should we not advocate, for economy and greater reliability, the use of electricity for this purpose? I have had pneumatically-operated circuit breakers* on trial for several years. The operating cylinders are certainly perfect in their simplicity; but we fear to put them into practice lest there should be condensation and freezing; and, moreover, it would be fatal if the compressed air failed at the critical moment, for which everything must all the time be maintained in perfect readiness, even though it occurs, perhaps, only once in six months.

Mr. Buist is one of the users who criticize the strengthening of switchgear, but he is also one of the culprits in putting increased power behind it. He asks for weights per kW of switchgear, transformers, and alternators. For a typical case, say a large power station stepping up from 11 000 volts to 33 000 volts, with the switchgear in the reasonable place, namely on the 33 000-volt side, these are as follows:—

Transformers	6·8 lb. per kW
Generators, including condensers, air pumps, etc.	39 lb. per kW
Switchgear	12·5 lb. per kW

The switchgear includes the feeder circuits, each of which has to be of nearly the same weight as the generator circuits.

Regarding Mr. Buist's constructional criticism of the separate-room power-station switch-house, I must admit that I would prefer to put the whole gear out in the open as a cheaper precaution against fire arising, for example, from the effects of bombs. The causes of damage in the past have, I believe, been principally insulation failures, which are curable when the possibilities are properly realized; but I foresee that in the future there may be failures in the operation of circuit breakers on short-circuits when under new conditions above the true ratings. If Mr. Buist likes to put it that way, it is a lack of faith in all the switchgear in use to-day, which in the future, on account of extensions and because of the grid, is likely to be over-stressed. I think that an increasing degree of automatic control will free operators for some more soul-inspiring occupation than the present-day monotony of standing-by and watching, and occasionally turning a handle.

Outdoor Switchgear.

Mr. Orchard would carry out circuit-breaking and high-voltage tests simultaneously in the open, so as to reproduce operation under the worst weather conditions. This is sound enough, but would need some staging, since test-bay bomb-proof enclosure, automatic fire-extinction, 2 to 3 times normal voltage, and the reproduction of a scorching hot day or a snowstorm, do not mix well together. I hope the introduction of metal-clad switchgear for outdoor use will in future remove some of the reasons for this proposal. A full study of the programme outlined by Mr. Leeson will show that in due course ordinary field tests may be checked by

* *Journal I.E.E.*, 1925, vol. 63, pp. 428, 447, and 465.

* British Patents Nos. 297012—1927 and 298272—1927.

calculation from the results of tests on the standard circuit. In the meantime, this may not eliminate the desirability of field tests; but they are very difficult to arrange for on a large scale. I have rarely found a supply authority prepared to put at one's disposal a complete system, with sufficient power behind to be of any use; and even if help is forthcoming the tests have to be so much curtailed that they are apt to give very misleading results when compared with the full measured work in properly designed test plant. The comparison is analogous to the difference between the hurried performance of an untrained amateur and that of a full-time professional.

Mr. Winfield makes a good case for housing metal-clad switchgear, and the reduced dimensions make it reasonable to think of doing so even at 132 000 volts; but the risks of deterioration will be no more than those to which open-type circuit breakers for the same voltage are already exposed on the grid. The bakelite to which he refers in comparing its behaviour in a cold and a warmed building was probably of a quality much inferior to that which is procurable nowadays. As to provision for fire-fighting, I think that, if required, this could be made just as effective in the open as within a building. This leads one to a consideration of men who might happen to be near the switchgear at the start of a fire; they would have a much better chance of making their escape from metal-clad switchgear in the open, and certainly the chances would be enhanced by the absence of live conductors. To quote Mr. J. L. Hecht *—and rightly so, because he has had experience of metal-clad 132 000-volt switchgear, although of a non-unit panel type—" Hazards to personnel are almost completely eliminated."

On the issue of " indoors or out of doors " for metal-clad switchgear, Mr. Winfield and Mr. Buist take opposite sides; and since they both advise those who pay the piper I leave them to settle the tune. Mr. Kidd prefers housing on account of expansion of compound in the sun. It is not an easy matter to provide for this expansion and for breathing of air spaces when compound is used; and I agree that the difficulty is reduced with indoor mounting, which is usual for switchgear of ordinary dimensions. For the higher voltages, oil-filling, with conservator tanks and breathers, provides for changes in weather conditions.

132 000-*volt Metal-Clad Switchgear.*

After all that has been learnt about metal-clad switchgear, it is a wonder that Mr. Coates and Mr. Blandford should still anticipate difficulty in making extensions to it. Do they have trouble with metal-clad switchgear for ordinary power-station voltages? If not, they should have no reason to confess to any anticipation of difficulties, either in extensions or in maintenance, when the same principles are applied to higher voltages. Mr. Hecht records† that " the carrying on of constructional work is simplified and expedited," and he goes so far as to claim that metal-clad switchgear has a large salvage value when the growth of the system compels replacement.

* J. L. HECHT: "Development of the Waukegan Station of the Public Service Company of Northern Illinois," American I.E.E. Paper No. 32M9. (An abstract of the paper appears in the March 1932 issue of *Electrical Engineering*.)

† *Ibid.*

Mr. Trencham refers to some 132 000-volt equipment in which oil-immersed isolating switches and earthing contacts were used, with, in addition, air-break withdrawal plugs and sockets. I understand this relates to the American arrangement that I illustrated diagrammatically in Fig. 33, in the absence of full information* when writing the paper. I note that Mr. Trencham does not agree with the duplication of isolation to which he refers, although it is apparently a safeguard approved by the users. I would point out that practically both features are embodied in the new proposal as illustrated in Fig. 35 of the paper. In this design the central isolator is of the plug-and-socket type, and in addition there is an oil-immersed isolating and earthing switch co-operating with it.

Mr. Blandford, referring to Fig. 35, says he would not care to trust his life to mechanical interlocks, and prefers a visible isolation before engaging on any inspection or adjustment of the contacts in a circuit breaker. Mr. Trencham also refers to this point. There is much to be said in favour of visible isolation; but enclosed isolation, with definite and positive earthing, if the earthing is also visible, is just as effective. In the design shown in Fig. 35, a definite and visible isolation may be secured by the entire removal of the circuit breaker, if the additional trouble is thought to be worth while.

Replying to Mr. Blandford, my reference to further development (page 289) relates to prospects of using the metal-clad principles for more than 66 000 volts, when the circuit breakers will be heavier owing to increased clearances. They would not necessarily be overhung. Fig. 14, which is associated with Fig. 21, indicates the alternative. I think the interlocks can be made just as immune from derangement as in any of the better-known forms of metal-clad switchgear, of which it is a characteristic that the compact arrangement of parts renders interlocking more substantial than on the known forms of open-type switchgear. I do not anticipate Mr. Blandford's suggested difficulty of breaking charging-currents on any device used on Fig. 21, since all the contacts are in oil, as shown in Fig. 26. The advantage of space reduction is again that which applies to all metal-clad apparatus, particularly when it is to be enclosed within a building. As compared with the open type, the reduction is permissible because of the convenience it affords in inspection and maintenance while adjacent panels in close proximity are alive, and even out of doors the space consideration is important in congested areas.

Replying to Mr. Winfield, I am satisfied that the designs shown in the paper will bring the initial cost of the production of metal-clad switchgear very close to that of the open types now used on the 132 000-volt grid, and that, when information is available on the cost of maintaining the respective types, the disparity will turn the scale entirely in favour of the metal-clad type.

Some speakers complain that switchgear has become too bulky, and plead for reduction. I think we are apt

* E. C. WILLIAMS: "Electrical Design Features of Waukegan Station," American I.E.E. Paper No. 32—57 (published since my paper was written). (An abstract of the paper appears in the March 1932 issue of *Electrical Engineering*.)

to overlook the fact that the increase is due to the great increase in power and voltage of recent times. At all events I hope that the present proposals will be accepted as evidence of a tendency to reduce dimensions. For example, Fig. O compares the type recommended in the present paper with the vertical-lift-out oil-immersed-contact type of switchgear in accordance with my earliest proposals* for oil isolation. The lower part of the illustration shows the duplicate circuit-breakers. The upper part corresponds to the circuit breaker illustrated in Fig. 35 of the paper, which allows an oil-break change-over for the duplicate busbars and thus requires only one circuit breaker per unit, and also avoids conductors from the two busbars in the same chamber. It does not follow that this design is final; but it does show progress in the economical replacement of bare-conductor switchgear for such voltages as 132 000 volts.

In reply to Mr. Coates's statement in Manchester about the conversion of a 3-switch group mesh sub-station into a 5 or 6 group mesh, I cannot think that he has given full scope to his imagination, because it is eminently simple and safe to open the ring for the short period during which the new connections are being made to the additional panels, which would previously have been erected in safety alongside. He suggests that the footnote to Fig. 34, relating to the bypass, is "more plausible than complete." It is not plausible: it is true, because it represents not only common but

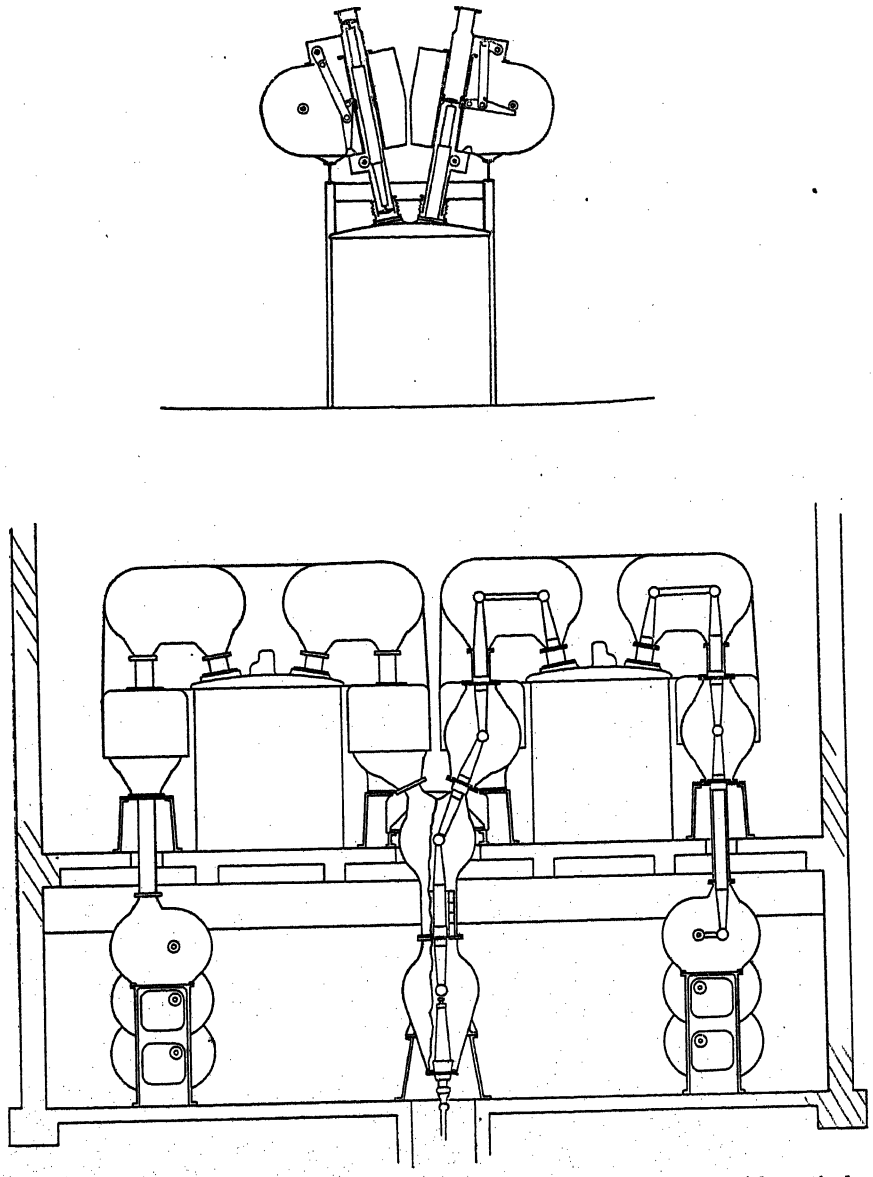


FIG. O.—Comparison of type of switchgear recommended in the paper with vertical-lift-out oil-immersed-contact type.

* British Patent No. 110808—1916; see also Figs. 8 and 9 of my British Association paper, 1927, which forecast the somewhat expensive type of switchgear now adopted by Mr. Coates and Mr. Evans for 66 000 volts.

universal practice with metal-clad switchgear. On straight metal-clad switchgear the need for bypasses has not been found, even in the largest power-station equipments, and so it is also reasonable to suppose that the same maintenance considerations would apply to metal-clad switchgear for 132 000 volts arranged like any other duplicate-busbar change-over job. If the footnote is incomplete at all, it is because it does not elaborate on the amount of attention likely to be required with the open type of construction, and does not emphasize the dangers that arise during cleaning and maintenance. Already there have been fatalities. To clean an open insulator or to do maintenance work on an open-type circuit breaker or isolator involves not only the opening of an isolating switch but also the preliminary provision of a clearance of about 15 ft., which necessitates very difficult screening or the shutting-down of complete sections. All of this, with the accompanying risks, is avoided if all the conductors are completely covered when alive, as they are in the alternative metal-clad construction.

My objection to a bypass in an ordinary duplicate-busbar equipment is that it adds to the initial cost and complicates the operation. Both these items are worth considering in view of the demands from many speakers for economy and simplification. Moreover, the advantages of metal-clad construction should be given full and free scope, and it should not be burdened with parasites that have developed because of the limitations of open-type construction.

I do not quite know what is behind Mr. Coates's reference to the isolating bushing of Fig. 35, to the effect that it strongly resembles the patented type used on some sections of the British grid; but it is only fair that any inference tending to deprecate British initiative should be nailed down once and for all. Mr. Coates, at my request, has kindly given me a reference to the patent,* and I find that it is of American origin. It does not anticipate the British patents on the movement of the central conductor or bushing for isolation. It makes no reference whatever to metal-clad switchgear, nor is it intended for isolating purposes. In fact, it is only a very ordinary bushing with a hollow interior through which a flexible conductor passes so that the top part of the bushing insulator can be removed if the porcelain surface or bakelized interior has to be replaced. This can be done, when it is applied to switchgear, without removal of the current-transformer chamber or of the switch contacts. There are objections to the arrangement, even as a component of an open-type switchgear device, but since I am discussing metal-clad switchgear, to which the invention does not refer, it is only necessary for me clearly to remove any wrong impression on the question of origin, which might otherwise arise from Mr. Coates's remark. An arrangement with a plug instead of the patented flexible conductor is the natural means of attaching a metal-clad cable to power-transformer terminals to enable the cable-sealing to be done outside and the conductor to be plugged in without disturbing the terminal connections of the transformer winding. The bushings shown in Fig. 35 were designed for 132 000 volts, and their diameter is consistent with standard practice for open-type switchgear. The place for current transformers is relatively a small point. On ordinary metal-clad switchgear they are not usually placed on the busbar side of the circuit breaker, but if this is absolutely necessary in order to include the circuit breakers in the protected zone in duplicate-busbar equipment of the type shown in Fig. 35, the current transformers could also be readily duplicated and placed over each connection between the circuit-breaker main contact and the busbar.

My conclusion is that Mr. Coates either had not really given thought to the possibilities up to the time of this discussion, or has been misled by approaching the design along unsuitable lines.

* British Patent No. 290651.

Purity of Oil.

I agree with Mr. Grove on the need for avoiding the use of semi-fluid compounds, on account of their attraction for moisture, and I also agree with what he says about loose, floating, fibrous materials in oil. I think it is necessary to carry out high-voltage type tests with oil of high electric strength (45 to 50 kV), because oil with a low or variable electric strength would interfere with the obtaining of the requisite fundamental data on the design and performance of the insulation, particularly in respect to puncture test. On the other hand, routine works pressure-tests to check quality of manufacture are not made at 20 kV, as Mr. Grove suggests, because the pressure tests of B.S.S. No. 148 are based on a 30-kV value. Mr. Grove and Mr. Orchard refer to risks of moisture in oil. Mr. Winfield also draws attention to condensation of moisture in circuit-breaker tanks, and the possibility that it may mix with the oil. I see no objection to Mr. Orchard's proposal to tap off oil from suitable places for examination, and for clearing away moisture. Given taps not likely to leak, it would be a good plan to fit them even on circuit breakers, when the oil could be circulated through filters and dryers while the panels were in service, without interfering with the supply. At one time I suggested that the warm oil from transformers should be circulated through the switchgear, so serving the dual purpose of keeping the switchgear warm and cooling the transformers; but I think that the idea has not yet received full consideration in suitable quarters.

Voltage Measurement.

The coming of the condenser coupler appears to have expedited improvements in voltage transformers. Both Mr. Ross and Mr. Coates refer to transformers with special windings to equalize capacitance stresses, but since the conductors must be continuous I cannot overlook the possibility of a burn-out on the primary turns. The saving grace of the condenser coupler is that it avoids the use of fuse protection, and the removal of the protecting fuse in the transformer circuit suggests imitation of the practice adopted for condenser couplers. The condenser coupler is a condenser insulator pure and simple, requiring no high-voltage protection, but in my opinion it is unwise to omit such protection on the high-voltage side of a voltage transformer. I believe it to be common knowledge that in America recently a serious

fire was started on a 132 000-volt voltage transformer, which was without this protection. There is nothing to prevent a conflagration if a high-resistance arcing fault is allowed to persist inside a transformer tank. The voltage transformer is the weakest part of the whole system, because it is a place where fragile high-voltage and low-voltage conductors must be brought into close proximity. The insulation must run the same voltage-stress risk as that of a large power transformer, in which, however, there is more room and the conductors are more substantial. It would appear to me to be unfortunate if the introduction of the condenser coupler for light instrument measurements were to bring about any impairing of the safety of the system by the removal of the voltage-transformer fuse merely as a result of price competition. Mr. Cranmer refers to the secondary connections. It is here that the condenser coupler scores, because if the secondary circuit becomes short-circuited no harmful effects would occur on the high-voltage line or on the high-voltage side of the coupler, whereas a similar fault on a voltage transformer may cause a burn-out of the high-voltage winding, whether or not it is provided with fuses. I agree that the output of a condenser coupler may not be as great as that of a voltage transformer; but, so long as it is sufficient for instrument and protective-gear purposes, this does not constitute an objection to the condenser coupler. Mr. Coates's implication that the condenser coupler requires adjustment with varying burdens is unfounded; the secondary apparatus inherently provides automatic regulation with the same accuracy as the voltage transformer.

Busbars.

I agree with Mr. Wilson that the tubular form of busbar is theoretically ideal as a conductor from the points of view he has illustrated in Figs. E and F. I have considered using tubular conductors, but the square or " box " formation of conductor was adopted because of its practical advantages and its close approach to the theoretical ideal. In metal-clad switchgear, one of the important factors is the ease and efficiency with which busbar sections can be jointed to each other and connections can be taken off to branch circuits. From this point of view the " box " formation is definitely better and more convenient than the tubular. In practice, the four conductors forming the " box " are bonded together along their length by metal spacers, and so conduction of heat does take place between the conductors, and the actual distribution of heat approaches the ideal obtained with the circular form more closely than Fig. F indicates.

Fig. 28 and Mr. Wilson's discussion, taken together, reply to Mr. Kidd's request for further information about busbars and temperature-rise.

Correlation of Breaking Capacity and Voltage.

I am glad to have Mr. Trencham's support of my proposal to place a limit upon power-station switchgear current by stepping up to high-voltage busbars when the larger breaking capacities are required. Other speakers have expressed their approval, and I am convinced that it would be a great benefit to switchgear design to eliminate awkward large currents. Mr. Winfield goes farther than the paper, and would alter the factor to 1/75 against my 1/125. I suggest a compromise in the nearest practical ratings as follows:—

Maximum breaking capacity for main circuit breakers	Maximum voltage (3-phase)
kVA	volts
1 500 000	22 000
1 000 000	11 000
500 000	6 600
250 000	3 300
50 000	660

These values would impose a reasonable limit on the ability of the circuit breaker to close on short-circuit, as required by Mr. Trencham, and would reduce the section of copper for circuits and feeders, as required by Mr. Winfield; and they would also tend to reduce the heating of the framework and busbars of metal-clad switchgear, as discussed by Mr. Wilson and other speakers.

Mr. Kidd wants to take voltages higher, and I would agree with him. In reply to his question, a voltage of 12 000 volts for 1 500 000 kVA is on the border-line of convenience. It has been employed by my Company, and so has 6 600 volts for 1 000 000 kVA (as shown by the tests in Appendix II); but I would prefer the 11 000-volt limit given above for 1 000 000 kVA. I am now practically in agreement with Mr. Mellonie.

Switching Capacity.

(*a*) *Rate of Rise of Restriking Voltage.*—A marked feature of the discussion is the frequent reiteration of the theory, propounded and explored by Dr. Slepian, of the effect on the critical happenings at the arcing contacts of a circuit breaker of the rate of rise of restriking voltage during each zero-current pause of the arcing period. This evidence of the wide reading of Dr. Slepian's works is a well-merited compliment to him. In keeping with his theory, I have proposed that circuit-breaker ratings shall be based upon a common standard of severity. The measure of severity at any given line voltage is the amount and duration of the current, both because of the mechanical stresses it brings to bear upon the conductors, and because of the static stresses occasioned by the thermal effects of the arc. Current is therefore the foremost factor in the ascertainment of ratings. It is controlled by the efficacy of the breaking devices and by the incidence of the voltage. The former is a matter of forethought, experience, and trial; but, as Mr. Pearce confirms, the latter depends upon the constants of the test circuit, which determine the rate of rise of the restriking voltage. Hence, in the proposed standard test-circuit (Appendix I), the lengths of conductors are to be kept as short as possible in order to reduce the self-capacitance of the whole test-circuit to a minimum, whereas the greater lengths of the conductors on a system increase the capacitance, and thereby introduce an easement in the stress of circuit breaking. Mr. Leeson has

dealt with this fully in his discussion, which confirms what Mr. Ferguson and Mr. Trencham have both observed, namely that tests in the field are less severe than those on a test plant. This affords an element of security to the user. The fact that circuit breakers operating on a system have a large amount of capacitance in parallel with the breaks may account for their satisfactory behaviour in positions where the vicinity short-circuits are apparently greater than the true ratings of the circuit breakers as proved on an individual test plant.

Mr. Blandford accuses me wrongly of glossing over the vital few micro-seconds after the zero at which the arc is extinguished. In addition to Mr. Blandford, Mr. Coates, Mr. Ferguson, Mr. Trencham, and Mr. Pearce, all make inferences about the rate of rise of restriking voltage; but they will see that "rate of growth" is referred to on page 301, and my expressed desire is to establish a standard test-circuit that will control the happenings at this critical moment. For this reason, the restriking-voltage interpretation (page 319) is most specific.

Mr. Leeson's clear and constructive contribution will do much to establish the constants for the standard test-circuit, and when we have reached an agreement in Great Britain the next step will be to make a move to secure international uniformity.

(*b*) *The Standard Test-Circuit.*—Mr. Coates wishes to compute test-results from readings direct from the oscillograph, but in common with others he declares the rate of rise of the restriking voltage to be the important factor, rather than its amplitude. He realizes, however, the unfortunate difficulty that exists in measuring this factor, at any rate for the present. Hence there seems really nothing left for him but to agree with me in taking its equivalent from the test-circuit constants. This requires a determination on a standard basis, and when this is agreed upon the performance results will be computed simply from the oscillograph current-record.

Mr. Coates suggests that standard pressure and travel recorders are also essential. This may be so, if the intention is to compare different makes on the basis of the data so furnished; but, interesting as that might be, it is hardly essential, since the factors do not affect the test-circuit standard of severity. Travel and pressure records would only have to be standardized if it were necessary to standardize the details of the design and operating characteristics of all circuit breakers; but that is not the present intention. We shall make quite sufficient advance if we standardize the meaning of rating as compared with test and service performance. When the purchaser is assured in this way, he will not need to compare tank-pressure tests, speeds of breaks, and a host of other items, as he probably does now in a rough and ready endeavour to work out for himself, and in his own way, what the standard test-circuit should do for him on scientific lines in the future.

Mr. Coates is surprised "to see that it is usual to generate direct from 3 300 to 22 000 volts." I almost hesitate to take him seriously, for he must know that there is direct generation at 3 300 volts, and at the upper end of the range the proposals, if anything, do not go far enough, because, as he must also know, there is already direct generation at 33 000 volts at Brimsdown. I submit that, considered widely enough, Proposal (xi) (*a*) is true; and there is the further point, which is really the main issue, namely that the test circuit for the ascertainment of standard ratings, within the range of voltages specified in Proposal (xi) as a whole, must be of one standard of severity; and the proposals do actually recommend a practically convenient basis of division into groups.

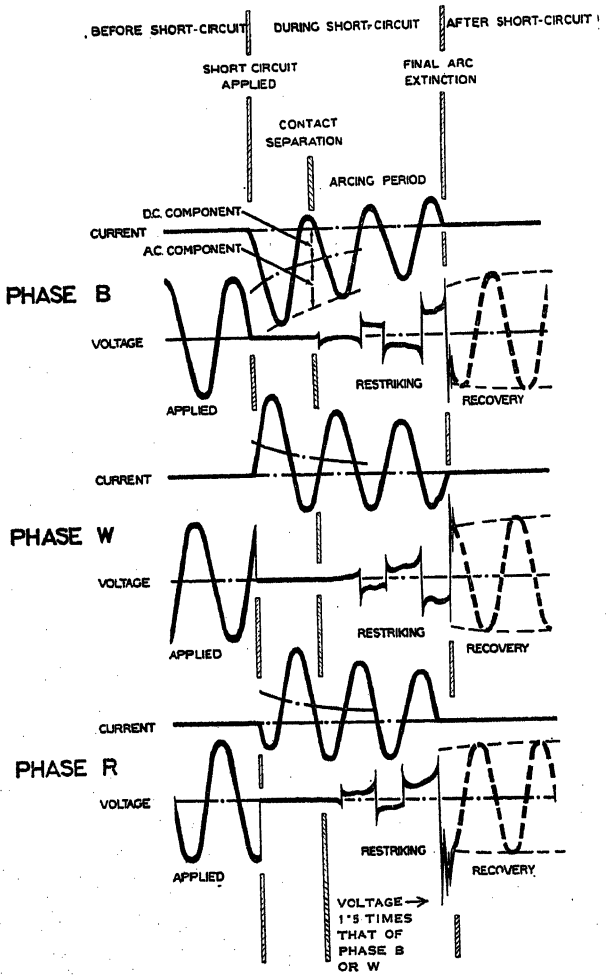


FIG. P.—Diagram of typical 3-phase asymmetrical short-circuit, illustrating (*a*) Factors for calculating performance; (*b*) Voltages for determining severity.

NOTE.—Neutral insulated; recovery voltage 80 per cent; power factor 0·1 lagging; arc extinguished first on red phase. Final restriking-voltage transient shown exaggerated in duration.

(*c*) *Definition of Terms for Voltage Phenomena.*—Although I appreciate the point of Mr. Blandford's definitions, the voltage when the current ceases is no longer restriking but recovering, and the recovery then becomes an intermediary stage to restoration. But, on the other hand, the voltage is not fully restored until it settles down, or up, as the case may be, to the applied voltage. Hence, considering everything, I trust that he will help to avoid confusion by using the following terms, which are illustrated in Fig. P, to define the different voltages

that exist in a circuit before, during, and after a short-circuit on a circuit breaker in that circuit.

(1) *Applied voltage* is the R.M.S. value of the normal-frequency voltage that exists at the initiation of the short-circuit.

(2) *Restriking voltage* is the series of high-frequency voltage transients that exist at the zero-current pauses during the arcing period, together with the final and more pronounced high-frequency transient that begins at the instant of arc-extinction. Its magnitude is measured on a peak-value basis, and its severity also depends upon its rate of rise.

(*d*) *Appendix I and B.S.S. No.* 116—1929.—Mr. Coates and Mr. Pearce are in agreement with the paper in referring to the need for cathode-ray oscillograph investigation into the restriking voltage phenomena, and for a clarification of the means of interpreting an oscillograph record in terms of a kVA performance. Mr. Coates is aware of the vagaries of the voltage phenomena, and yet he suggests that all that is necessary to make B.S.S. No. 116—1929 serve our present purpose is to define recovery voltage. He proceeds, however, to make the solution more remote by proposing the indefinite method of taking the mean of the first two

TABLE A.

Relative Short-circuit kVA Performance Values obtained by Different Methods of Calculation from the Factors illustrated in Fig. P.

Method	The sum of the products in each phase of			Neutral	3-phase kVA broken	
	Current components		Voltage		80 % V	100 % V
					per cent	per cent
1	British and American	A.C. and D.C.	Rated line/$\sqrt{3}$	Insulated or earthed	100	100
2	British and American	A.C. and D.C.	Recovery: at arc extinction on *each* phase	Insulated	93	117
				Earthed	80	100
3	British and American	A.C. and D.C.	Recovery: at arc extinction on *last* phase to break	Insulated or earthed	80	100
4	British and American	A.C. and D.C.	Separation	Insulated or earthed	95	100
5	Continental	A.C.	Rated line/$\sqrt{3}$	Insulated or earthed	75	75
6	Continental	A.C.	Recovery: at arc extinction on *each* phase	Insulated	70	88
				Earthed	60	75
7	Continental	A.C.	Recovery: at arc extinction on *last* phase to break	Insulated or earthed	60	75
8	Continental	A.C.	Separation	Insulated or earthed	71	75

(3) *Recovery voltage* is the R.M.S. value of the normal-frequency* voltage that exists during the interval between the end of the final restriking voltage-transient and the restoration of the applied voltage.

These terms appear to be generally acceptable to other speakers in accordance with the suggested definitions, and are also used in the proposed sense both in the paper and in this reply to the discussion. In support of the term "restriking voltage," I would emphasize the fact that the voltage-transient that occurs at each current-zero, and the voltage-transient that occurs at arc extinction, as shown in Fig. P, are in reality the same phenomena. The only difference is that the transient that occurs at arc extinction is more pronounced than those that occur during the arcing period, because the re-establishment of the arc eliminates the greater part of the transient. In other words, the restriking-voltage transient is successful in its unwanted efforts during the arcing period, but unsuccessful at the particular current-zero pause at which arc extinction occurs.

* Obviously, the frequency here called "normal" may differ slightly from the frequency of the applied voltage because of remanent effects of the short-circuit.

half-cycles following arc extinction, or, alternatively, the line voltage, whichever is the greater.

On the other hand, Appendix I of the paper recommends that the whole voltage characteristic shall be treated as a condition of severity, just as power factor is already treated. The criterion of performance is the value of the current made, carried, and interrupted, and so the method of measurement by current is the only definite one. Current values, however, are not easy either to memorize at different rated line voltages or to associate with plant sizes, and it has therefore been the practice, and is still necessary, to rate circuit breakers, and to state performance, in kVA. Values of kVA at the best are only arbitrary, and, as shown in Table A, are widely divergent according to the many different ways of ascertaining the voltage multiplier. Appendix I recommends the use of rated line voltage, and when this is coupled with actual current measurements on a test-circuit of standard characteristics there will no longer be any doubt about the meaning of a declared kVA rating. It will be possible to compare all circuit breakers on a common basis, without the

delay that Mr. Coates anticipates will be necessary if the rate of rise can only be specified after research and measurement on an instrument not yet developed in a form suitable for practical service. Mr. Pearce infers that I may adjust the power factor of the short-circuit test-circuit to the value of 0·1 specified in B.S.S. No. 116—1929, and may so obtain an easier test, because the adjustment reduces the rate of rise of restriking voltage. Presumably he thinks that it always introduces additional capacitance; but, whatever the values may be, the practical experience remains that an easier test is obtained at a higher power factor. Moreover, the test-circuit, however it is adjusted to give the British standard power factor, must always be more severe than the working conditions of a normal power station, on account of the difference in the lay-out of the conductors. I accept as good humour Mr. Pearce's gibe about the frequency of the existing test-plant, which, as he infers, does not practice what the Appendix preaches; but it may nevertheless make a virtue of necessity, because of the claim that a test at 40 cycles is more severe than one at 50 cycles.

(*e*) *Ratings and Vicinity.*—The questions asked by Mr. Crocker, as well as by Mr. Haws at Middlesbrough, are very typical of what most users want to know at the present time. What rating of circuit breaker is suitable for particular positions on the system? Mr. Winfield also refers to the different methods of rating, and particularly to variations between Great Britain and other countries in this respect. As Mr. Leeson has explained, it may take years of research, but eventually it will be possible, if the standard test-circuit is established, to tabulate for the guidance of users the margins on standard ratings afforded by specific conditions of service. The amount of short-circuit calculated from the size of a generating plant and the impedance of a network to any particular circuit breaker on the system is the vicinity short-circuit, and when this is considered in relation to a standard circuit-breaker rating, as determined on a standard test-circuit, the easements, such as those due to higher power factor and lower rate of rise of restriking voltage, may be taken advantage of, either as additional margin for safety, or to effect the much-desired economy by way of selecting circuit breakers of a rating lower than the vicinity short-circuit. Purchasers having the knowledge that circuit-breaker ratings were based upon a standard representing the most severe conditions of service would be in a position to exercise with confidence their discretion in regard to the allowances to be made for the reduction in stresses occasioned by the easements afforded by working conditions. But it must always be remembered that these easements do not enter into the problem of closing on short-circuit.

(*f*) *Closing on Short-Circuit.*—Mr. Ferguson says he cannot understand my statement on page 302 about closing circuit breakers on short-circuit. What I wish to infer is that insufficient attention has been given to this subject in the past. Notwithstanding the inclusion of the "make" test in the duty cycle, it is still not infrequent to hear reports of test-demonstrations in which "make" tests are not included. Indeed, for large currents these are not so simple as might at first be supposed. It has to be remembered that the easement secured by the current-decrement in the short-circuit transient when breaking is not afforded when making a short-circuit. The "make" is against stresses due to electromagnetic and thermal disturbances set up by the first few waves at the maximum-current stage of the short-circuit transient. The short arcs occasioned by any slight chattering of the arcing or main contacts, or by any tendency for the plunger bars to pump, set up distortion, burning, and very high static stresses within the circuit-breaker enclosure. On occasion (Appendix II) these stresses have proved to be as difficult to deal with as those set up by breaking short-circuits. Hence I suggest that the reason for the apparent freedom from trouble on making short-circuits is the fortunate infrequency of the occurrence at full rating in practice. This rarity has led users in the past to overlook the necessity of providing for making-capacity as well as breaking-capacity in their specifications, and Mr. Ferguson will remember that it was not included in the British Standard Specification prior to 1929.

(*g*) *Tanks.*—Mr. Grove raises the very practical issue of round and rectangular tanks. I prefer the rectangular shape, because it gives a uniform space-allocation of tank volume for each of the phases, and allows room for an earthed metal conductor between phases without reduction of phase-to-earth clearances in a given tank volume. The vertical round tank tends to cramp up the phases, as Fig. Q shows, because of the waste volume over and above the required clearances to the tank walls on the middle phase, and owing to this, rather than for the reason of bad distribution of stress also suggested by Mr. Grove, the earth between phases may have to be cut out. Again, it is not possible always to resort to vertical insulation only, because the plunger bars supported by insulating rods must be braced to withstand the mechanical forces between phase conductors during the passage of short-circuit current, and this introduces a horizontal insulating surface, which may be less than that of the usual rectangular-tank design owing to the narrowed centres for an equal tank volume. Metal for metal, however, the round tank is stronger, or, in other words, the rectangular tank of equal strength must be heavier in metal. Mr. Wilkinson prefers the round type, because some inferior old types of rectangular shape have burst under short-circuit tests; but the same thing applies also to round tanks when they are not strong enough.

The most efficient use of the round shape for circuit-breaker tanks is when the axis of the cylinder is horizontal, and not vertical, as advocated in the discussion. This is also illustrated in Fig. Q, which shows how the rectangular section of the horizontal cylinder across the plane in which the arcing contacts lie allows, as in the rectangular tank, not only for an equal clearance on all three phases, but also for an earthed attachment and metal barrier-rib between phases, for which there is no equivalent facility in the circular section of the vertical cylinder.

(*h*) *Tank Pressures.*—This brings me to Mr. Ferguson's statements about tank pressures. Hydraulic pressure-testing of circuit-breaker enclosures is a fundamental requirement, and at this stage of switchgear progress

it may seem surprising to some users that it should be necessary to mention the point at all. In some designs of circuit breakers, however, a hydraulic test may be difficult to make, because the gasket joint between the tank and the top-plate, although thought to be quite good enough for switching-service, would leak too much to allow the requisite high steady pressure to be attained. Mr. Ferguson's machine would be very helpful here; but I prefer to use a tight, machined, flanged joint, which is cleaner, as well as flame-tight in service, and allows for hydraulic pressure-testing by the usual process of injecting pressure by means of a force pump. Mr. Ferguson's suggestion of tank type-testing by exploding gunpowder has been referred to at Institution discus-

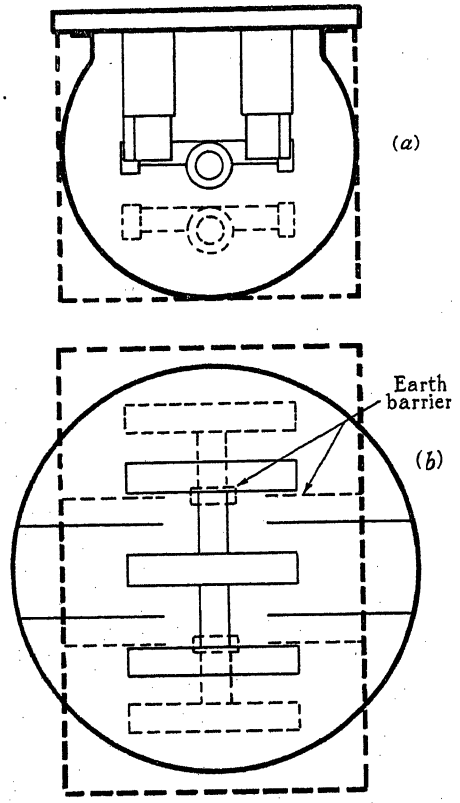


FIG. Q.—Comparison of circular and rectangular tanks:—
(a) In vertical plane.
(b) In horizontal plane.

sions in the past, and was in fact the only means available 20 years ago when my Company originated the strong enclosure as a simple solution of the breaking-capacity problems with which we were then faced on the North-East Coast.

Referring to Fig. 38, Mr. Ferguson says that there is no proof that the impulse pressure of 950 lb. per sq. in. was safe on a tank made for a steady hydraulic pressure of 150 lb. per sq. in. The proof is that the tank withstood the test without permanent distortion; the records are available among many others of similar occurrences. The tank was the ordinary commercial article; and, should doubt still exist, Mr. Leeson's records of explosion tests, the first of which were made in 1920, confirm authentically a high ratio between the momentary impulse pressure and the steady hydraulic pressure.

(*i*) *Air-cushion.*—Mr. Ferguson may feel satisfaction with lower tank pressures under test conditions, and these he doubtless secures, when plain contacts are used, by means of a large air-cushion and a domed top-plate. On the other hand, I prefer comparatively small air-cushions, in order to produce the very result he wishes to avoid, namely a high internal pressure, the reason being that all the pressure available is necessary, particularly at low fault-values, to suppress the arc quickly, and incidentally to eliminate the risk of secondary explosions of large volumes of gas. Experiments made at Hebburn on circuit breakers with air-cushions of about one-third of the total enclosed volume show that the arc may continue for twice or thrice as long as with more normal air-cushions, and that the stress is actually more severe because it is sustained over a longer period of time. A brisk conflict, firm and unyielding, inflicts the least disturbance on the system. Indeed, the main virtue of boxed contacts of the explosion-pot or baffle type, when they are themselves strong enough to stand the strain, is that they keep up the pressure on the arc. The unyielding tank, backing up the oil walls surrounding the arc, does the same thing, but from a greater distance.

(*j*) *Mr. Ferguson's other questions.*—Replying to Mr. Ferguson's other questions in detail, and in the order in which they were raised, I would say: (1) The test-pressure record shown in Fig. 38 was taken, as I said at Manchester, with a Collins micro-indicator. This is of British make, and I know of none more accurate or more reliable for practical service testing. (2) The pressure record shown in Fig. 38 was obtained on Test No. 257 (page 327), the power broken being 180 000 kVA, and the rating of the circuit breaker 100 000 kVA. (3) Assuredly I should be in favour of allowing purchasers to examine curves of performances. (4) A long series of tests was taken on the 100 000-kVA circuit breaker at and below normal rating. They were easily performed, and presented no item of sufficient interest to be worth space in the *Journal*. Certainly none was omitted to cover defects. (5) It is true that one of the many tests, namely No. 100, resulted in a damaged tank at 133 per cent of normal rating. The cause, a mechanical defect after 14 tests, is explained on page 323, and it must also be noted that these circuit breakers, fitted with plain contacts and strong enclosures, stood well up to 240 per cent of their rating. (6) As to the maximum breaking capacity advocated for hand operation, the confidence that one would have in operating a circuit breaker direct must depend upon the strength of the enclosure, its competence to withstand sustained arcing, its condition, and the chance of its never being closed on a short-circuit greater than its making capacity. In the ordinary operation of a circuit breaker there are no risks, because it would not be opened at a time coincident with the breaking of short-circuit current; and therefore direct operation has been used for circuit breakers of quite large capacity, up to, say, 250 000 kVA or even more. As a general rule, however, I have found it reasonably economical to have remote operation for circuit breakers of 75 000 kVA

rating and over. It is really a matter for the user to determine on the basis of his operating conditions and on considerations of economy. (7) There is a mass of information available on the tests recorded and other tests; and the only intentional omission is again due to there being a limit to the amount that can conveniently be included in the *Journal*, bearing in mind the necessity to keep the data within the limits of general interest. An indication of arc lengths is given in the record of arcing periods in half-cycles, and a typical pressure curve is shown in the paper.

(*k*) *Failures.*—In support of the paper, Mr. Ferguson showed " what breaking capacity is " by putting on the screen lantern-slide illustrations of experiences as a result of which buildings were destroyed owing to the use of inefficient oil circuit-breakers; presumably the tanks were too weak to withstand the operating stresses. But it must not be thought that such explosions are brought about only by oil circuit-breaker troubles. On the contrary, there are records of destruction of buildings occasioned by arcing outside of oil circuit-breakers; and thus, although oil may be contributory, and may have the effect of prolonging a fire, it does not follow that it must be looked upon as the sole cause of explosions. I have yet to learn of any destruction of buildings occasioned by circuit breakers operating on short-circuit within their rating, when the strengths and dimensions of their tanks have been such as were recommended in my earlier papers and discussions. These were illustrated on a slide shown during the reading of the present paper, and are reproduced here as Fig. R. In my opinion, what has to be feared most is a failure of insulation causing sustained arcing, and this is more likely to occur on exposed insulators than on insulators immersed in an insulating medium in metal-clad chambers. At Manchester, Mr. Ferguson cast doubt upon the reliability of a large proportion of the circuit breakers at present in service, and Mr. Wedmore says that " there never was a time when so many supply engineers were uneasy as to the rupturing capacity of their switchgear." I hold no brief for the majority; my only claim is that the tests recorded in the paper show that a typical British design of plain commercial form does perform satisfactorily with " reasonable consistency."

(*l*) *Factor of Safety.*—Mr. Ferguson and Mr. Blandford ask what factor of safety I would suggest for rupturing ability. (I notice that there is no reference to " making.") A safety factor of $1\frac{1}{3}$ to 1 without permanent distortion should suffice; but this is a very wide question, which cannot be as easily dealt with as can that of the factor of safety of an ordinary mechanical structure. I suppose it depends upon the degree of permissible injury to the circuit breaker. I think circuit breakers should withstand double their rating on breaking without damage of a kind that would endanger human life. I say this not because I fear they may be so badly selected as to be used where the vicinity short-circuit is likely to attain this overload value, but because they may be subjected to unforeseen sustained arcing conditions, to meet which some such precaution is necessary. The factor of safety on " making " circuits involves consideration of the excess of the maximum making-current over the normal breaking-current, owing to the time factor introduced by the decrement of the short-circuit transient. Personally, I think it dangerous to grade down required ratings on the strength of the time-limit factor, but a circuit breaker selected on the basis of a 1-second time-decrement might have to " make " up to as much as 6 times its breaking current, depending upon the reactance of the generator. On the curve recommended in the paper (page 319), namely Fig. 2 of B.S.S. No. 116—1929, the maximum asymmetric making-current would be greater than the breaking-current; and, given certain coincidences of faults, a circuit breaker may be called upon to separate its arcing contacts when carrying a current of this higher value.

(*m*) *Effect of Power Factor.*—Replying to Mr. Grant's comments on the effects of power factor, my conclusion that the demand upon a circuit breaker is greatest at

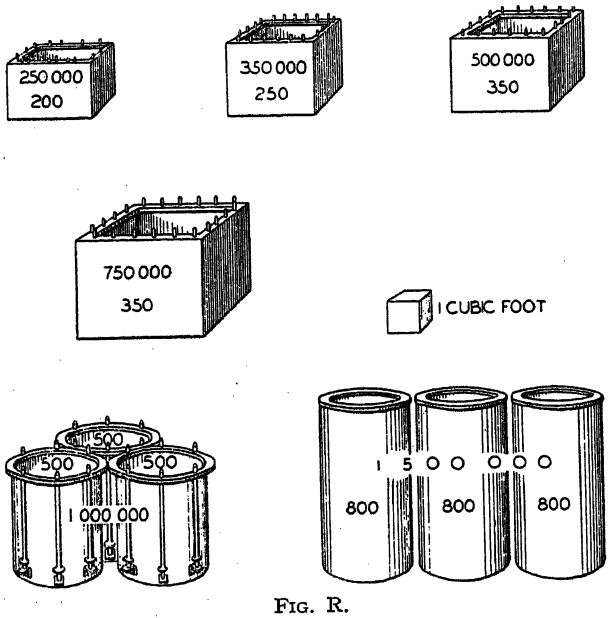


FIG. R.

Numbers represent rated kVA breaking capacity of complete circuit breaker, and pounds per square inch hydraulic test-pressure of individual tanks.

a low power factor is based not upon a few tests, but upon a large number made at Hebburn on circuit breakers of different sizes at power factors varying between 0·1 and 0·5. These show very conclusively that the nearer the power factor is to zero, the greater is the severity. This seems to be in accordance with the effect to be expected from the change in the magnitude of the voltage at zero current. Mr. Crocker asks about ratings for a vicinity short-circuit of 300 000 kVA at 0·5 power factor (presumably this is the short-circuit power factor and not the normal-load power factor). Considerable easement should be expected from the 0·5 power factor as compared with ratings determined upon a 0·1 power factor, in addition to whatever benefits may accrue from field service being lighter than test service, and it is reasonable to suppose that a circuit breaker of smaller rating, with a proved factor of safety, would serve the purpose well.

(*n*) *Earthing on the Test Plant.*—It is apparent that the proposal in Appendix I (page 320) is not clear to

Mr. Coates. It is not to be understood as meaning that it is British practice to insulate the neutral point below 66 000 volts. The contrary is known to be true, but insulating the neutral point on the supply side of the test circuit for the purpose of the test covers also the prevalent practice of earthing below 66 000 volts through a "comparatively high resistance," and in addition makes the test conditions more severe than actual service conditions (see Mr. Leeson's Fig. D). Mr. Ferguson does not favour tests with the neutral earthed, because an earthed neutral greatly relieves the stress. The Appendix agrees with this view, but makes an exception for voltages of 66 000 volts and upwards, because this complies with the practice in service on the British grid.

Stress Limitation.

(*a*) *Types of Contacts.*—Mr. Trencham is disappointed that the progress of circuit-breaking devices has not been more fully treated. He was not present at the reading of the paper, or he would have seen the series of diagrammatic representations of the plain, boxed, and blast devices shown on the screen. These are reproduced here (Figs. S to Y) as a brief bird's-eye record of the various devices known when the paper was written. Of these, for very large currents, and in view of the need for making as well as breaking, the plain contact has much in its favour for simplicity and all-round general service, particularly when some form, such as that shown in Fig. V, affords discrimination between making and breaking, the make being on a separate anti-chattering contact at close centres, and the break on ordinary heavy contacts at wide centres. This reduces the combined electromagnetic and thermo-explosive kick-off forces on making, without interfering with the use of these forces to the full for breaking. I suggest that to make 250 000 peak amperes on a 6 600-volt circuit would be difficult with circuit-breaker contacts of the boxed class, but it has been proved by Test No. 419 (page 327) to be possible with plain contacts. The Grant quenched-arc type of boxed contact, although at first it showed promise on lower-power tests, was unsuccessful at higher powers. (This answers a question raised by Mr. Stedman at Middlesbrough.)

My reply to Mr. Grant is that at the time of writing the paper, information about the "cross-jet" contact* had not been published, and the results of the most recent experiments with the E.R.A. "baffle" contact,* of similar kind, were not officially accessible to me. These contacts have side openings to direct turbulent oil and gas across the path of the arc. Since the paper was written tests made at Hebburn on a device similar to the "baffle," to which the name "turbulator" has been given, go a long way towards showing how to meet the demand for circuit breakers, in accordance with Mr. Wedmore's forecast, having two to three times the present breaking capacity without increase of dimensions, presuming that outside dimensions only are in question. These tests were made on an existing 250 000-kVA circuit breaker with the addition of special boxed turbulator contacts, and were carried up to 500 000 kVA at 11 000 volts. After a few failures a correct design of box was arrived at, and the 2 to 1 margin over rating was secured without any sign of distress. Table B describes briefly the results of representative comparative tests on the 250 000-kVA circuit breaker with turbulator contacts and on another of the same rating with plain contacts.

TABLE B.

kVA broken at 11 000 volts	With turbulator contacts			With plain contacts		
	Arcing period, in half-cycles	Total length of arc	Steady pressure on tank-sides	Arcing period, in half-cycles	Total length of arc	Steady pressure on tank-sides
		in.	lb./sq. in.		in.	lb./sq. in.
160 000	2·0	2·13	15	4·5	5·50	100
273 000	2·0	2·50	45	4·0	4·75	125
350 000	1·0	2·00	40	1·5	3·25	150
500 000	0·5	1·00	40	Not tested at this value		

The recovery voltage during the tests was of the order of 80 to 85 per cent of the line voltage.

(*b*) *Limits of "Make."*—The rating is incomplete, however, without the "make" performance, and to the requisite greater cost of the contact boxes there must be added the cost of improved mechanism at those voltages where the limit of the existing mechanism is the maximum current carried when making a short-circuit corresponding to existing ratings. With the same disposition of conductors, an increase of 2 to 1 would increase the "make" kick-off forces in the ratio of 4 to 1, and a trebling would imply a 9 to 1 increase. This may be possible with some existing types, but if the design is already within fine limits, the increase of breaking capacity by the mere addition of special contacts does not accomplish everything, nor does it represent the only extra cost. Although the addition of such arc-control devices, when they are applied under suitable conditions, does increase the margin in breaking capacity, we have still to ascertain the limits beyond which such devices, taking into account circuit-making as well as circuit-breaking, may introduce complications in design tending to produce mechanical weakness and possibly dangerous sustained arcing.

Time is required to obtain all the test data necessary

* H. PEARCE and T. T. EVANS: "Some Notes on Oil Circuit-Breaker Design and Performance," paper read before The Institution 17th March, 1932.

* British Patent No. 366998.

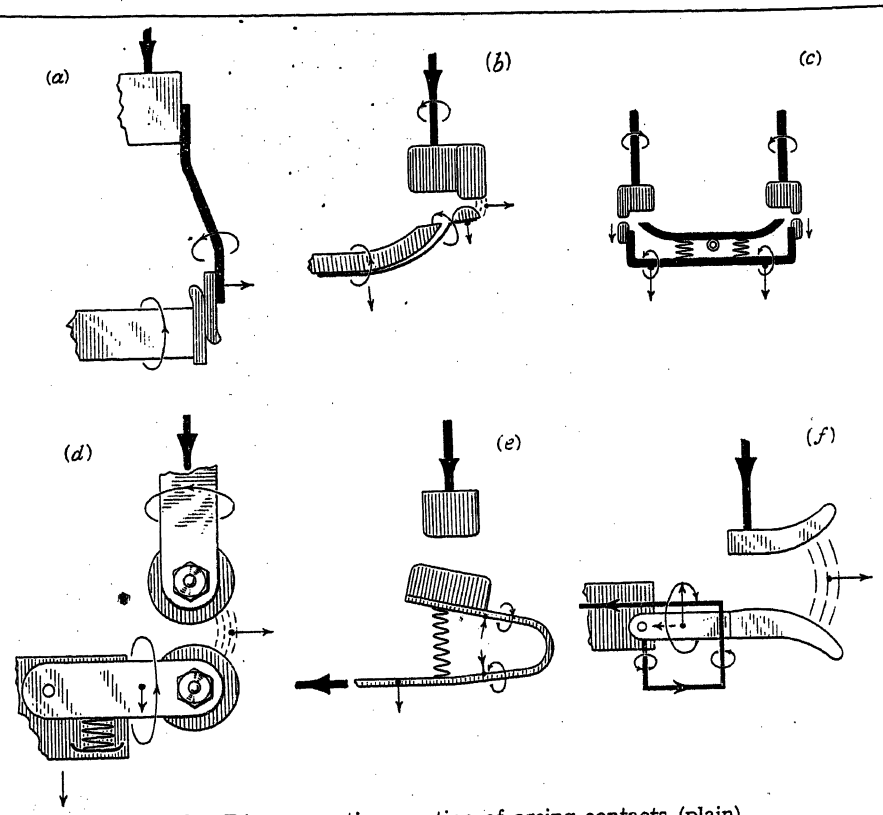


FIG. S.—Diagrammatic operation of arcing contacts (plain).

(a) Plain finger sparker. (b) Plain leaf butt. (c) Butt.
(d) Roller butt. (e) Anti-chatter butt. (f) Anti-chatter butt (with arcing horns).

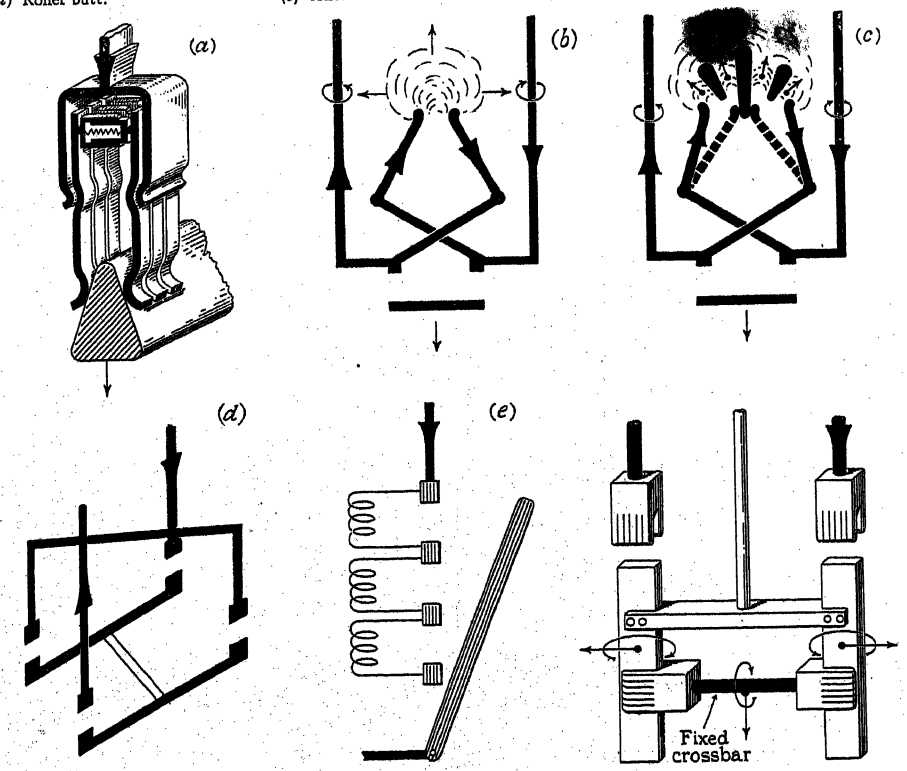
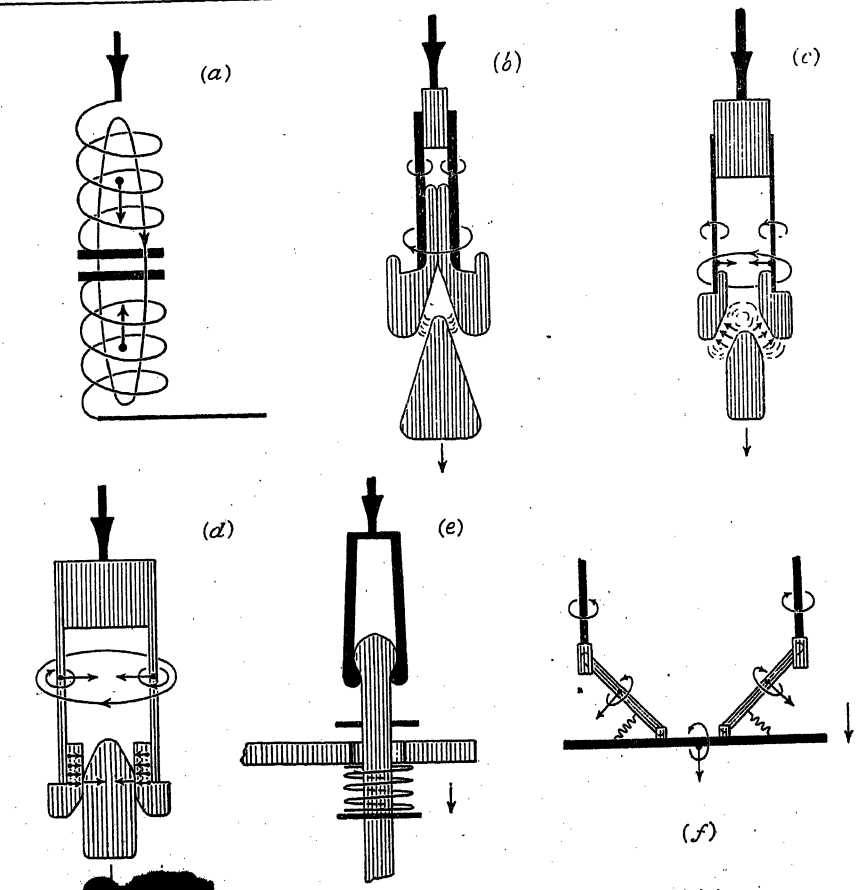


FIG. T.—Diagrammatic operation of arcing contacts (plain).

(a) Dashpot finger (multiple point). (b) Vertical blowout (single break). (c) Vertical blowout (split arc).
(d) Multi series break. (e) Reactance (resistance) break.



—Diagrammatic operation of arcing contacts (plain).

(a) Solenoid contact (anti-chatter).
(b) Wedge finger.
(c) Self-grip finger (anti-chatter).
(d) Steel self-grip finger (anti-chatter).
(e) Snap-pin contact.
(f) Snap-blade contact.

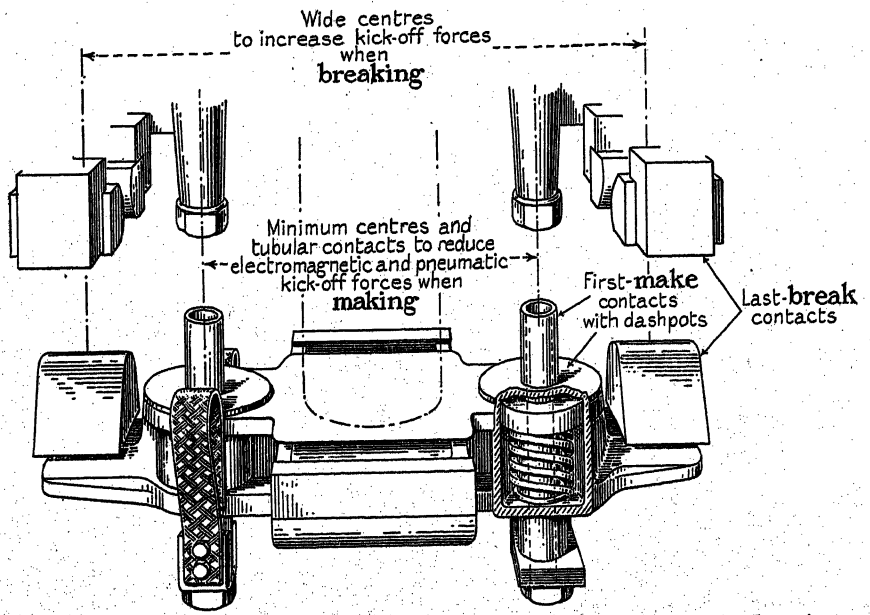


FIG. V.—Make-and-break discriminating contacts (main contact not shown).

to determine the safe limits in making and breaking current, and to show how to avoid the bursting of boxes, the harmful effects of which would obviously far more than counterbalance any intrinsic advantages of the boxes themselves. Meanwhile it is safe to say that the present explosion-proof tank enclosure must continue to be used, not only as a second line of defence against accidents to the more crowded inside parts, but as an aid to breaking by maintaining the high pressure required in the immediate neighbourhood of the arc for the shortening of the arcing period.

So far I have found that, for existing ratings of the order of 1 000 000 kVA and upwards for normal generating-station service, contacts of the plain type have the advantage of the simplicity for which Mr. Trencham calls, and, moreover, they embody this desirable feature to an extreme degree. In comparison with the multitude of alternative contacts and blasts, nothing can be simpler or cheaper to produce and to maintain for metal-clad switchgear than plain contacts in robust metal tank-and-top-plate enclosures. That this is so is especially clear when it is remembered that these enclosures are still required, no matter what form of intricate contact may be devised with the object of increasing the margin of safety in breaking capacity. Even if it is possible, by the addition of a boxed-contact device, to add 50 per cent to the test-performance, the rating of the circuit breaker should still be of the order of 1 000 000 kVA, since some risks have been introduced by the additional devices.

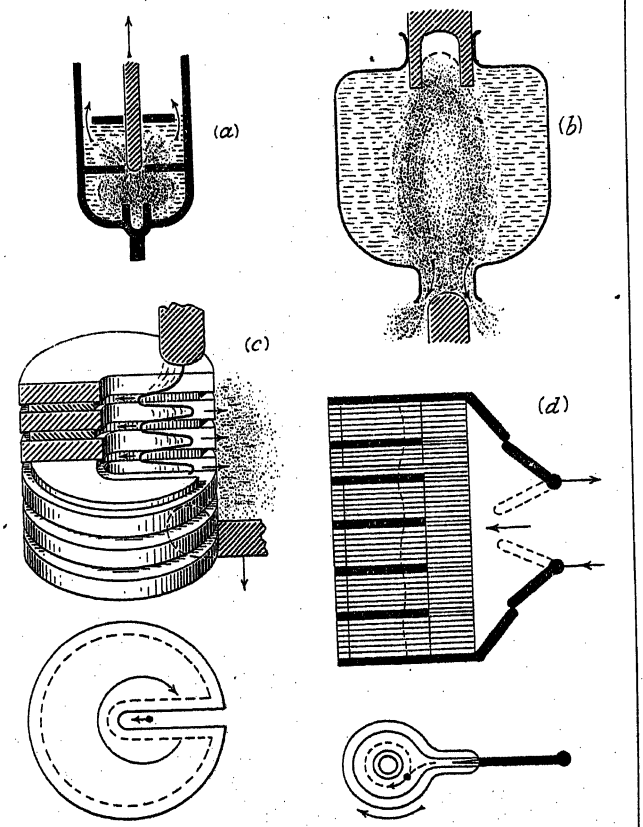


FIG. W.—Diagrammatic operation of arcing contacts (boxed).
(a) Baffled explosion pot. (b) Plain explosion pot.
(c) De-ion grid. (d) De-ion air break.

(c) *Oil-less Circuit Breakers.*—Mr. Rissik deals with circuit-breaking on the "expansion" principle, in accordance with which de-ionization occurs in a saturated vapour. My endeavours to procure a circuit breaker of this kind for test have not been successful, and hence my knowledge of the operation of expansion circuit-breakers is no more than is given by published information, in which, incidentally, short-circuit current-making characteristics are not described. It would appear that for large currents it is the practice to have a separate air-break current-switch in parallel with the expansion device. This, with its connections, and with the choke devices found to be necessary for current-sharing, adds to the number of bare conductors and insulators; and it also tends to delay fault-clearance. Moreover, no saving in cost over that of ordinary oil circuit breakers has apparently been made as yet.

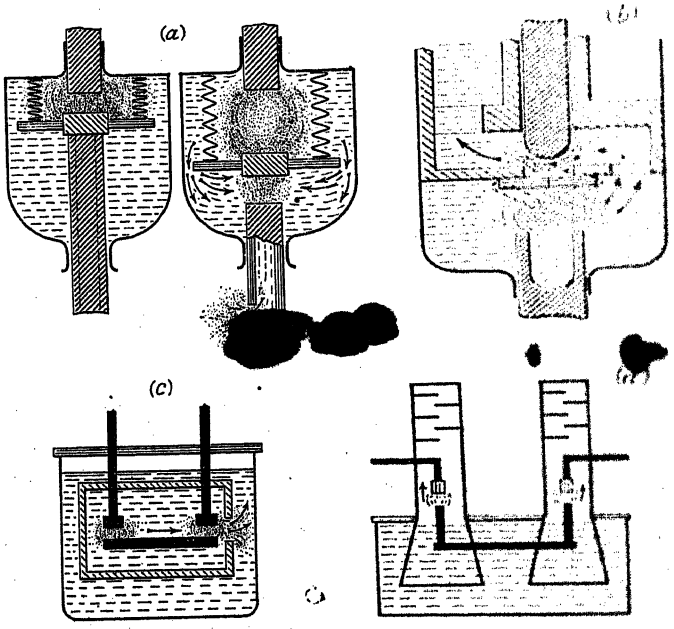


FIG. X.—Diagrammatic operation of arcing contacts (blast).
(a) Oil-bast explosion pot. (b) Gate oil-blast.
(c) Oil-blast baffle. (d) Semi-immersed.

It has been said that the degree of expansion created by the current must not be less than a definite minimum, below which it may be insufficient to extinguish the arc by the expansion process. Considerable attention appears to have been given to this subject. One interesting proposal* for dealing with it was to use a second chamber acting as a water-resistance switch in parallel with the expansion chamber. If this were adopted, the likeness to the old water-break switches would be more striking, since over a larger range the current would be broken by means of a plain water-break.

In my opinion the expansion type, like the air-blast type, will not make progress in its present form because security of insulation is an even greater primary consideration.

* British Patent No. 364345, accepted 7th January, 1932.

tial than perfect circuit-breaking. The insulation has to withstand stress during all the time that the circuit breaker is in circuit, whereas the circuit-breaking device itself may operate only very infrequently. Complete immersion in oil or compound is an invaluable preservative in metal-clad construction, whereas the introduction of moisture is the very antithesis of the durability of insulation. The attempt in Germany, first with air-blast circuit breakers, and then with expansion circuit breakers, to remove troubles that it may be thought can arise from oil, may itself lead to running into more serious trouble because of exposed conductors and insulation.

that surface I would expect them to melt down immediately on making circuit. Metals that will not weld together are of course chosen.

Saving Switchgear.

Mr. Highfield refers to the question of dealing with 750 000-kVA short-circuits on existing 50 000-kVA switches. This is indeed a serious problem, and I do not know how it is going to be solved. Some form of group-switching (page 304) may be used to meet it. The conditions of such situations will be made clearer by a detailed study of the vicinity short-circuit at each switching-centre on the system, and of the easements

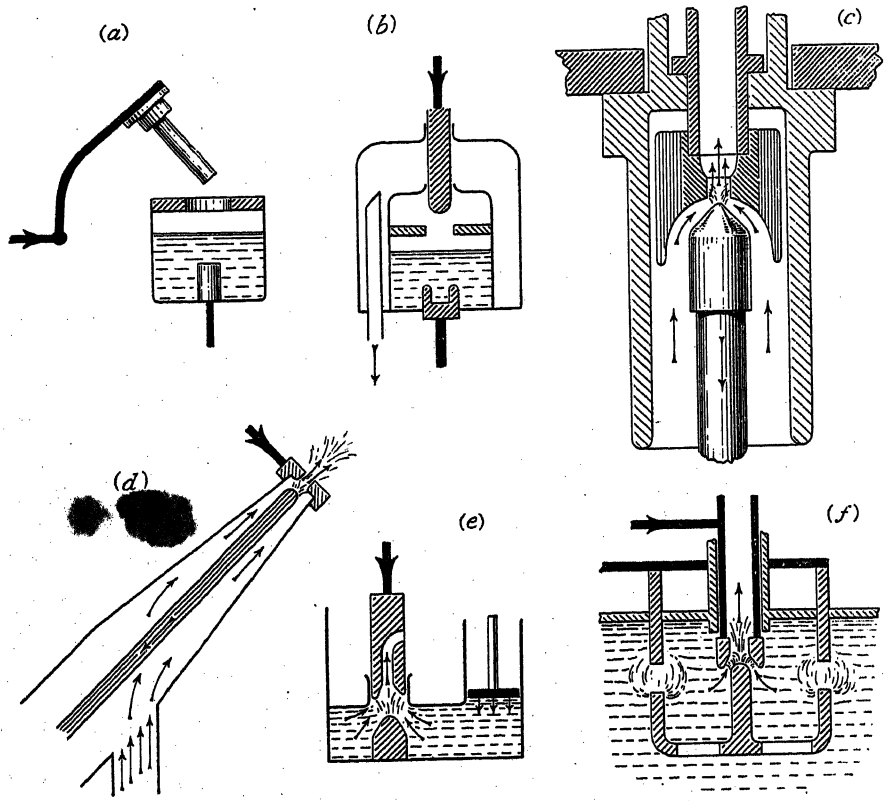


FIG. Y.—Diagrammatic operation of arcing contacts (blast).

(*a*) Old water break. (*b*) Liquid (water) expansion switch. (*c*) Controlled air blast.
(*d*) Open-air blast. (*e*) Impulse oil breaker. (*f*) Oil blast.

(*d*) *Multi-breaks.*—Mr. Cranmer asks about the performance of multi-breaks. These are included in the plain-contact class, and for high-voltage working probably represent by far the greater proportion of British practice to-day. Their function, in addition to increasing the speed of break, is to bring about an increased efficiency in the utilization of the oil volume; and their performance is satisfactory. The future may settle the present rivalry between multi-break contacts and some form of boxed contact for high-voltage service, in which the problems of heavy current are not so acute as at lower voltages.

(*e*) *Steel Arcing-Contacts.*—I have not come across the difficulty found by Mr. Grant, that globules on steel arcing-contacts cause incipient arcing on heavy-current circuits. The globules are generally away from the contact-making surface; but if any were to appear on

to which I have already referred. The fuse is an economical device in some places of lesser importance, when a small system is linked up with a large one, because a small fuse has the characteristic of limiting the amount of current that it will pass instantaneously. If the fuse is small enough, and the vicinity short-circuit is large enough, the fuse will blow before the first wave of the short-circuit transient has time to reach its maximum peak value. As another solution, where maintenance of supply is of prime importance, Mr. Highfield might find some scope for the "synchronizing-at-the-load" system (Fig. 40, page 303) as a means of reducing the required breaking capacity of the main circuit-breakers, since the load itself is used as a limiting reactance. I would also refer him to the "secondary network" mentioned by Mr. Trencham, which seems to be very much to the point.

Mr. Kidd claims that the credit for the idea of the single-switch substation attributed in the paper to Mr. Beard belongs to a Manchester engineer. The paper refers to a development, illustrated in Fig. 39, of the particular form of substation introduced by Mr. Beard, and called at the time "single-switch." The fault lies in the fact that the title is too general. There are obviously many ways of effecting economy in cutting down the number of circuit breakers, but the scheme referred to by Mr. Kidd is different in principle from Mr. Beard's, in that the circuit breaker is used for group control of the transformer circuits, whereas Mr. Beard uses it as an automatic protective device for sectionalizing a ring main. As a still earlier item in the history of switchgear connections, also in Manchester, Mr. Kidd will probably remember a single-switch application where a number of high-voltage feeder circuits were closed and opened through a single water-break resistance switch.

Safety of Men Working on the Line.

I am in full agreement with Mr. Crocker on the need for simplicity, and for greater care on the part of the manufacturer for the convenience and safety of operators. A multiplicity of types must be a great handicap, and earthing devices have not always been tried out sufficiently by designers to avoid taxing the patience of the users. It is with this in mind that alternative designs have been recorded in the paper.

Fault-Current Limitation.

Mr. Buist refers to the ohmic value of earthing resistors. When applied to circuits working at voltages of the order of 6 600 volts they are usually of low resistance, and I agree that, unless the earth-plate contact-resistance is taken into account, erroneous values for the protective-relay settings will be obtained. In comparison with earthing resistors applied to circuits of voltages of the order of 33 000 volts, for which resistances of about 19 ohms may be used, to pass currents of approximately 1 000 amperes, the earth-plate resistance can usually be neglected, since it is small compared with that of an earthing resistor. To overcome the uncertainty introduced by the earth-plate resistance in networks at voltages of the order of 6 600 volts, the earthing resistor should have a slightly smaller resistance than the total value aimed at, so as to allow for the resistance of the earth plate. The earthing resistor must be such that the earth-current passed on the occurrence of a fault is equal to at least twice the fault-setting of the protective relays on any part of the system, thus giving a factor of safety of 2.

Tripping Batteries.

In reply to Mr. Shipley, even in the tropics the renewal of the electrolyte should not need to be more frequent than once every two years. It is probable that the infrequency of the renewal is contributory to the trouble he describes. Nevertheless, it seems weak to change a type because of operators' errors in renewing with acid instead of with alkaline electrolyte. If such mistakes can be made now, is it not just as likely that alkaline electrolyte would be put into the acid cells, if they were adopted? I have heard of natives using starch for puddings.

I am glad to have Mr. McKinnon's correction on the construction of the nickel-cadmium battery,* and his confirmation of the possibility of using a trickle-charger for this type. It is to be noted that Mr. Grant finds the alkaline battery desirable in many ways.

Grid-Control Rectifier.

Mr. Taylor asks about a grid-control rectifier as a switch, and his question raises a new consideration of power-distribution problems. I understand that in place of each circuit breaker there would be a valve to carry the power current through a grid-controlled electron stream. Although this is an interesting thought, which may be realized in the future, the difficulties of carrying present power loads in this way make it impracticable for the time being. Presumably the circuit-breaking on this system would be done on the high-voltage side by a suitable control of the filament or grid circuit. Otherwise, I should say that switching unidirectional high-voltage current would be much more difficult than switching a plain alternating current.

Bakelite in the Tropics.

Mr. Orchard asks about reliability of bakelite insulation under semi-tropical conditions. Porcelain is frequently preferable, on account of its better surface durability; but a large number of bakelized-paper insulators have been supplied to tropical and semi-tropical countries and are giving satisfaction when immersed in oil or compound. When continuously exposed to a humid atmosphere, the surface of bakelite may require special treatment.

Cleaning Orifice Insulators.

Mr. Mellonie suggests a fitting to clean orifice insulators when they are alive. Such devices require great caution, and I consider it definitely preferable to leave cleaning alone until the conductors can be made dead and earthed. The trouble is that, however safe the fitting might be made, some person doing the operation would be only too likely to put his hand into the orifice in a moment of forgetfulness, perhaps to remove something that the fitting had left behind or that had not been cleaned away.

Automatic Isolation of Faults.

Limitation of Damage.

Mr. Winfield says that with modern machines it is now preferable to trip the main field-switch simultaneously with the main circuit breaker, instead of immediately after, as stated in the paper (page 308). I would welcome confirmation of this from the makers of generators.

Present-Day Practice.

One unusual feature of the discussion, perhaps satisfactory to the reader, is that no additional protective system has been put forward. This indicates that the subject is now written up to the point of saturation;

* Incorrectly referred to in the advance copies of the paper as "nickel-iron."

and it was reasonable to expect this state of affairs, seeing that the paper follows so closely on the full treatment of the subject in the recent discussion before The Institution, initiated in the paper by Mr. T. W. Ross and Mr. H. G. Bell.* The innovations of the last few years have now to be digested in practice; and I suggest that in the process of elimination of the unsuitable and protective system has been imported from abroad, and that the reactance (ratio-balance) system is "theoretically more perfect." The British developments introduced include: (*a*) Reactance instead of impedance as a basis of measurement; (*b*) instantaneous operation on faults over 70 to 75 per cent of the feeder length; and (*c*) a time-distance characteristic especially shaped to

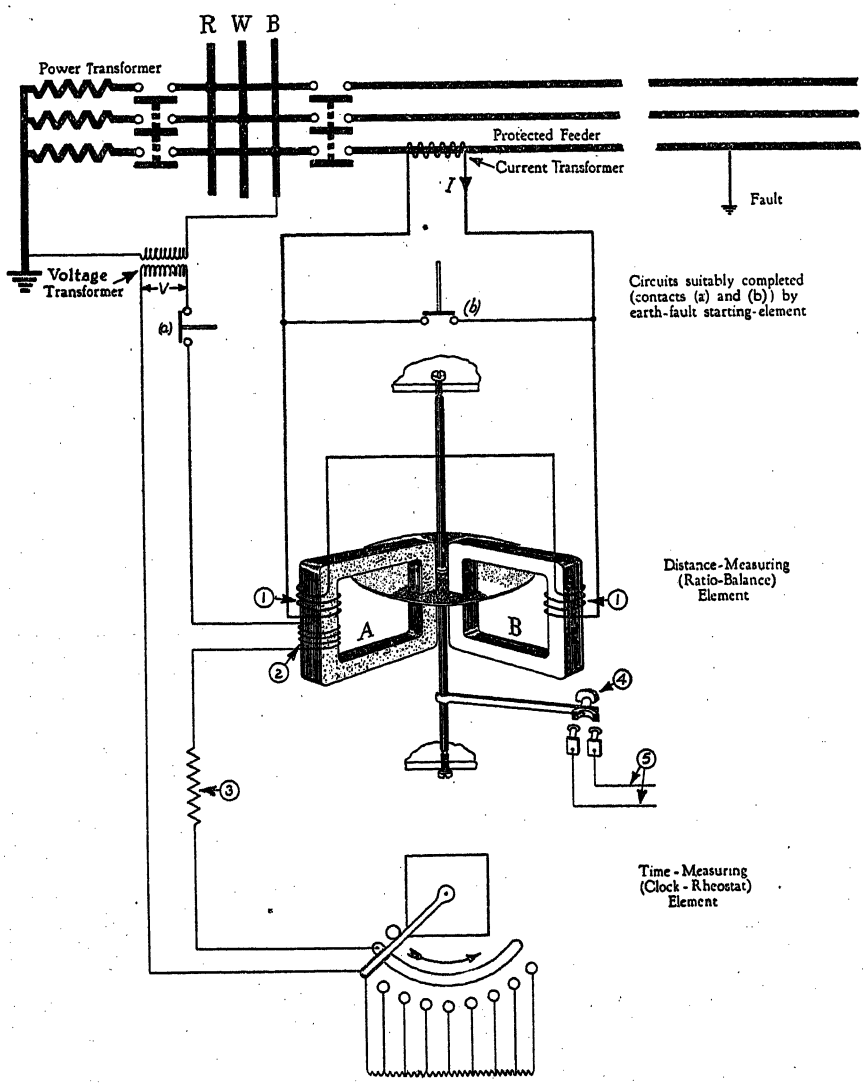


FIG. Z.—Diagram illustrating the principle of the time-distance discriminating unit of the reactance-type "ratio balance" protective system.

(1) Current coil. (2) Voltage coil. (3) Resistance. (4) Stop. (5) Trip circuit.

of selection for adaptability to situations and conditions, there will be many incidents and some "grief," and that an authorized and impartial body should collect, analyse, and study the experiences, in view of the great importance to the future reputation of electricity supply of continuity in all parts of the country when the whole national system is interconnected.

We have it on Mr. Ross's own frank admission that the experience of the impedance type of time-distance give an appropriate margin of time for faults on adjacent feeders. Mr. Ross, after referring to (*b*), asks, in effect, whether it is worth while to have the "theoretically more perfect" system for the sake of the remaining 30 to 25 per cent of the length. My answer is "Yes," because this is the most critical part for accurate discrimination. If the two systems are properly designed for their respective purposes, one is no more complicated than the other. Indeed, the main elements of the two systems, namely the time-distance discriminating

* *Journal I.E.E.*, 1930, vol. 68, p. 801.

elements, could hardly be distinguished from each other at a first glance if both were made by the same manufacturer, because the difference between them is merely in the method of utilizing the magnetic fields produced by the current and voltage coils. In the impedance system, each field provides its own torque, and these are put in opposition to each other; and in the reactance system illustrated in Fig. Z, in which the resistance-component of the impressed voltage is cancelled out by the very simple device of having a current coil (1) on the same limb as the voltage coil (2), the two fields co-operate to produce a single torque. The removal of the current coil from the limb referred to, the addition of shaded pole-tips, and the separation of the two magnetic fields for the purpose of a mechanical balance instead of magnetic co-operation, would make the reactance relay into an impedance relay. The difference between the two forms cannot rightly be described as a complication; indeed, if anything, the reactance relay is the simpler. With particular reference to Mr. Ross's impedance system, there is, in fact, in respect of actual total numbers of elements of all kinds, for equivalent service, nothing to choose between it as a whole and the ratio-balance system, which embodies the two advantages of a null method of distance measurement and accurate timing by means of a clock common to a group of elements protecting a feeder end, Mr. Ross's substitute for which is the less accurate device of an induction disc operating through a torsion spring in each time-distance discriminating element.

Mr. Ross suggests the possible need for additional "rejectors" (or high-frequency chokes, as they are called at B in Fig. 56) on the superimposed interlock system of protection, presumably because he fears that the signals may be short-circuited by the other lines. These may be necessary in some applications, but tests so far made on 66 000-volt lines and on 100 miles of 132 000-volt line have been satisfactory with rejectors on one line only, as shown in Fig. 56. Interference between adjacent sections is provided for by the use of different high-frequency carrier currents. To point out the dependence of the system upon the life of hot-cathode valves is perhaps a natural criticism; but Mr. Ross must not judge from ordinary domestic wireless experience. Wonderful as are the improvements that have been made, and great as are the future steps towards perfection that may be expected in this service, the valves used for it are comparatively of a low grade, whereas, to ensure reliability, the valves for protective gear, like those used in the valve repeater stations of the Post Office, are selected from the pick of all production. Reliability of operation is further obtained by provision for easy testing for deterioration of the valves and other apparatus, by periodic replacement, and by an automatic alarm in the unlikely event of an accidental failure.

Of Appendix III it has been said that the arrangement of electrodes used in the test does not correspond to practice, both because the gap was horizontal and because it was too long. But faults may occur between lines as well as from lines to framework, and, further, wind tends to elongate the arc, and the metal vapour from the fuse used to initiate the arc is not present in service. Hence the tests carried out are representative of average conditions. In addition, I think that Mr. Ross and Mr. Cranmer are not correct in assuming that the length of the arc remains the same as the distance between the initial flash-over points. In flash-over tests made with post insulators, an arc at only 20 000 volts travelled 14 to 15 ft. almost instantaneously along a neighbouring earthed rail, and what appeared to be metal from the live conductor was actually deposited on the burnt splashes of the rail at that distance away. Mr. Paul Ackerman, as a result of tests made in Canada, refers to the possibility of an arc of 1 000 amperes at 110 000 volts having a critical length of 370 ft. It occurs to me that Mr. Ross and Mr. Cranmer must be accustomed to think in terms of a voltage flash-over test with comparatively small power behind it; but the behaviour of an arc with a power system behind it is very different. It floats out and waves like a flag, and simultaneously with its fading away when it reaches great length another arc may instantly establish itself across the post insulator and follow a similar course. Tests have not been made with an actual chain insulator; but, judging from tests on vertical post insulators that have been made, the shape and type of the insulator, and its position, do not affect the resistance of the arc once it has been established. Mr. Cranmer raises the question of current values. The deductions of the paper (page 328) are based upon currents of the order of 500 amperes. If they were based upon the 200 amperes suggested by Mr. Cranmer, Fig. 76 shows that the errors of impedance protection given in the paper would be greatly increased. Mr. Wedmore suggests that the presentation would be simplified if the results were expressed in terms of voltage-drop per unit length of arc; but the difficulty is to measure with any degree of accuracy the length of an arc waving about violently in the air.

Mr. Ross asks how the R.M.S. values shown in Appendix III were deduced from the oscillograms. The test-circuit contained a large amount of impedance in series with the arc, inserted for the purpose of keeping the current in the circuit constant even when the arc-resistance varied, so that the distortion of the current wave-form was negligible. The slight distortion present in the voltage wave-shape was not taken into account in calculating the R.M.S. values, but the effect of neglecting the harmonics is very small, since they have to be added vectorially to the fundamental: a 20-per-cent harmonic affects the R.M.S. value by 2 per cent only. Further, the design of the ratio-balance (reactance) relays is such that the effect of wave-distortion on their operation is negligible in practice.

I have noted Mr. Ross's claim of satisfactory operation for impedance protection in Scotland. Future results, added to experience of operation with his type of protection in South-West England, where the arcing loads may be lighter owing to the greater distances of lines from large power stations, will be a deciding factor in this controversy of impedance versus reactance measurement.

Mr. Ross raises an interesting point about the possibility that the direct-current component of asymmetric

short-circuit faults may cause inadvertent tripping on Merz-Price balanced-voltage systems; but an asymmetric current entering one end of a sound section leaves it at the other end, and, whether or no there are direct-current impulses, the experience of a very large number of heavy-current balancing tests with the equivalent of very long and very short pilots shows that, if present, they are ineffective. The only abnormal frequencies that may cause inadvertent operation are those that do not pass through both ends equally, and the effects of these, when existing, are removed by tuning. I agree on the acid test of service, and hence I would stress the country's need for an impartial observation of results, because I feel that the issues involved are too great to leave entirely in the hands of competitive manufacturers.

Mr. Wilson, in his references to protective systems, deals particularly with the possible changes that we may have to make to get back to the starting-point such that all the high-frequency currents do pass through the restraining coil, it seems to me that their effect must be to increase the restraint on the operation of the relays under both healthy and faulty conditions, because the mechanical balance upon which operation depends cannot differentiate between frequencies. In a healthy section this increased restraint is necessary for stability; but unfortunately the same increased restraint will exist in a faulty section, with the undesirable result that the normal-frequency fault-current for tripping must be greater to an unknown and variable extent. This would mean that the McColl system does not comply with two fundamental requirements of protection, namely that high-frequency out-of-balance currents shall not adversely affect the stability of healthy sections, and that in a faulty section they shall not increase the normal-frequency tripping fault-current.

I, too, believe in the possibilities of split-conductor protection when applied to parallel feeders. If an

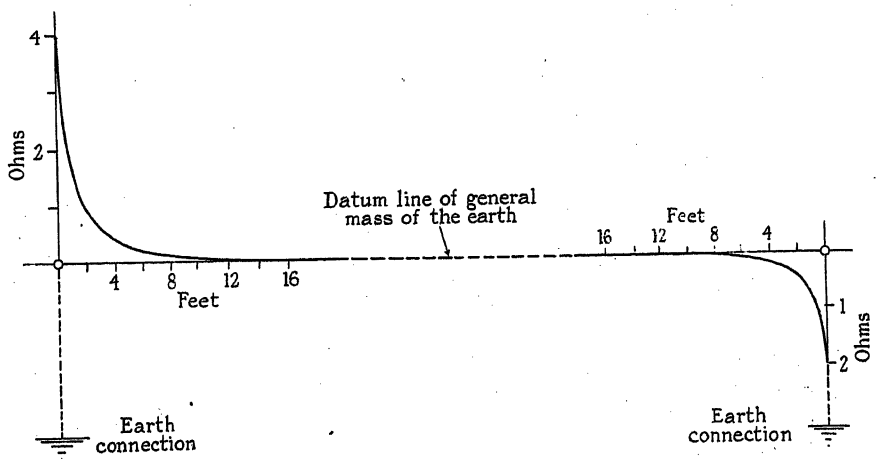


FIG. AA.—Diagram illustrating resistance-distance characteristics between two earth connections.
The ordinates represent the resistances between the points at which they are measured and the general mass of the earth.

of instantaneous release on account of the risk that plant may run out of step even with a small time-lag. He is hopeful of the carrier-current or superimposed interlock system, and suggests that the Kapp-Carrothers (duplex) scheme is of a similar type, and should also meet the conditions; but I understand that, so far, a similarly economical and practical method is not available for the transmission of signals by superimposed high-frequency currents with the duplex system.

Mr. Wilson claims that the McColl bias system of feeder-protection without tuning complications is quite unaffected by high-frequency surges, and that other vagabond and harmful currents all pass through the restraining coil of the relay, and hence stabilize the system instead of tending to make it trip. It is not clear that all the high-frequency currents will flow entirely through the restraining coil, and so conveniently avoid energizing the operating coil. It seems possible that the distribution of the high-frequency current through each coil depends upon the capacitance of the pilot wires, that is to say, upon their length, and it would appear that the pure McColl system must be subject in some circumstances to inadvertent tripping of healthy sections. If, however, the conditions are existing system has to extend the carrying capacity of its mains, nothing could be simpler, and at the same time more economical, than to put a new main alongside of the existing main, and to join them both up to the busbars through one panel. I think that new ring mains, as long as they are comparatively unimportant, might be protected by some time-class system, but when they become sufficiently loaded to warrant additional cables the reinforced sections could be cheaply and thoroughly well protected by split-conductor equipment.

Safeguarding Telephone Systems.

Mr. Bartholomew emphasizes the desire of the Post Office for the protection of its cables from the results of faults on power systems. He asks how the proposed figure of 50 yards was arrived at, and wishes to have details of tests. The 50 yards from the power-station earth plate, which should be on the outskirts of the building, was an empirical distance selected with a view to obtaining a piece of ground likely to give the necessary clearance from any other earthed metal in contact with the power station. Distance and resistance measurements, as shown in Fig. AA, have been made

between two dissimilar earths. Actually the potential difference between the ground surrounding each earth-connection and the general mass of the earth falls very rapidly in the first two or three feet, and becomes negligible within three or four yards.* The power tests mentioned in the paper are those referred to at the end of Appendix IV, which showed that the proposed precautions are adequate from the point of view of protecting relay apparatus from the effects of short-circuits on the associated high-voltage current transformers. Care is essential to avoid short-circuiting the fault-current paths by the lead sheaths of small cables, and it is valuable to have a record of Mr. Bartholomew's experience and conclusions. A case of trouble on pilot wires occurred in France owing to defective earthing, and damage to plant happens because of short-circuits initiated by lightning. Mr. Shipley's experiences in the tropics are a valuable contribution to this subject, owing to the greater prevalence of lightning there. Mr. Cox will note that his point about placing the spark-gap close to the switchgear is already provided for in the diagram, which reads: " Earthing device near switchgear."

Remote and Automatic Control.

Power-Station Control Boards.

Mr. Kidd's interesting ideal for future control boards is, I think, generally in line with the trend of examples shown in the paper, which are mainly based upon work actually in use or in hand. I am not so sure as he is that the telephone type of control switches and cables is sufficiently substantial; but the reduced space-factor must be a considerable aid to operating engineers, and will advance reliability so long as connections are not so close together that the operation of the controls or maintenance and cleaning work leads to inadvertent operation or signals. Referring to vertical-scale illuminated instruments of the shadow type in a row, I do not, of course, mean to suggest that they can do more than supplement the customary summation instruments.

Tandem and Radial.

Mr. Cox confirms the paper in the prospects of converting central-control indicating systems into complete operating control, but he prefers to use adapted telephone apparatus. Such equipment may be more flexible, as he says, but only in the " meccano " sense, in that it consists in the main of a multitude of standard telephone parts, whereas the alternative centrovisory-control apparatus has been specifically designed on the basis of mechanical units for its individual operating features, and possesses all the flexibility it needs for its essential purpose, which is the control of power systems. It is not correct to claim generally that a combination of telephone parts is speedier in its operation. Indeed, in some cases it is slower, owing to the cumulative number of individual impulse operations making up a given total indication or operation. In eliminating multitudinous relays operated by chains of impulses by the substitution of fewer mechanisms, centrovisory control aims at simplicity and reliability, and its circular system-diagram enables a large number of circuits associated with any one station to be indicated clearly in a minimum useful width of control panel. Mr. Ross also thinks that centrovisory control is less flexible than the combination of mass-produced telephone parts that performs the same functions. In reply, I would say that, so long as it can be made in sufficient quantities to be economical, it is refreshing to get away from the monotony of the telephone devices. As to the diagram, it is as simple and rational as the face of a clock.

Except possibly for railways, the radial system is more in conformity with normal geographical location, particularly in relation to central control. The continuity of full service is of great importance, and a breakage of a pilot in a tandem-controlled system would appear to dislocate the control to a much greater degree than in a radial system. For instance, seeing that the most likely location of a break or disconnection is in the more densely built-up areas of the kind to be found in the neighbourhood of control stations, the entire tandem system would be jeopardized by such a fault or break in the pilot.

Furthermore, although I agree with Mr. Cox about extended use on circuits of smaller powers, I suggest that there is likely to be considerable congestion of messages on a 2-pilot tandem system such as he has proposed, comprising 30 stations each with 10 operations. I am greatly interested in Mr. Winfield's remarks on the tandem system of pilot control. It is obvious that congestion of signals and the accompanying heavy duty on the telephone equipments cause wrong operation, which can only be avoided by the radial system upon which centrovisory control is based.

The Mimic Measurement of Vicinity Short-Circuits.

I am obliged to Mr. Smail for the analysis he has given of the requirements of a calculator suitable for the grid, and I would explain further that the two separate types of faults to which he refers are dealt with in the calculator shown in Fig. 66 by having the removable links constructed with concentric fittings in such a way that there are actually two distinct circuits, which represent the earth-fault and phase-fault conditions described by Mr. Smail.

Mr. Grant visualizes mimic calculator boards that will measure all characteristics and phenomena at any point of the system, including the change of impedance during the decrement period. These can be furnished; it merely needs someone to come forward who is prepared to pay the cost. In the meantime, the reproduction of impedance by ohmic resistance with direct-current power supply seems to suffice, and at times, I fear, to exceed users' ideas of price; and, after all, the information about resultant impedance thus obtained is a very great step in advance.

In conclusion, I would thank all those who have taken part in the discussion, including the Middlesbrough and Dundee members, the reports of whose remarks are, unfortunately, not available. There have been over 250 points raised in the discussion alone, and whether they have been super-critical, or due to mistaken reading, or constructive, they have all helped to show the need for a better understanding of the problems, and therefore they have all served a useful purpose.

* " Practices and Methods in A.C. Substation Grounding," N.E.L.A. Publication 256—20, New York.

THE PENETRATION OF ALTERNATING MAGNETIC FLUX IN WIRE ROPES.*

By T. F. WALL, D.Sc., D.Eng., Member, and C. H. HAINSWORTH, M.Eng., Associate Member.

(*Paper first received* 13*th January*, 1931, *and in final form* 19*th January*, 1932.)

SUMMARY.

When a wire rope is arranged in a laminated magnet yoke and magnetized by alternating current in accordance with the arrangement of magnetic circuit which has been described in a previous paper,† it is of importance to know how the magnetic flux becomes distributed across the section of the rope. In order to obtain some experimental data on this question, a sample of wire rope was constructed with a built-in search coil surrounding each layer. By an examination of the oscillograms obtained from these search coils the flux density has been obtained for each layer of the rope for two values of the a.c. supply frequency. By means of ballistic tests the flux density has also been obtained for each layer when the wire rope is magnetized by direct current.

INTRODUCTION.

In a previous paper† one of the authors gave an account of the principle of action of an electromagnetic apparatus which was designed in the Electrical Engineering Department of Sheffield University for testing for mechanical flaws in wire ropes, the excitation of the testing magnet system being obtained by means of alternating current. The form of magnetic circuit which is used in the rope-testing apparatus as described in the previous paper will be understood by reference to Fig. 1, which is reproduced from that paper. A ⊔-shaped laminated iron yoke is provided with an exciting coil, and tunnelled holes pass through the projecting limbs, the length of each of these tunnelled holes being large as compared with the diameter. The diameter of the rope under test is considerably smaller than the diameter of the tunnelled holes, so that there is a large clearance between the rope and the holes. Since the length of the tunnelled holes is large compared with the diameter, the flux density in the air-gap will be small and it is possible to obtain a high flux density at the section XY of the rope by means of a relatively small number of magnetizing ampere-turns. Typical proportions for the yoke and rope under test are shown in Fig. 1.

In the previous paper reference was made to the problem of the penetration of alternating magnetic flux

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1929, vol. 67, p. 899.

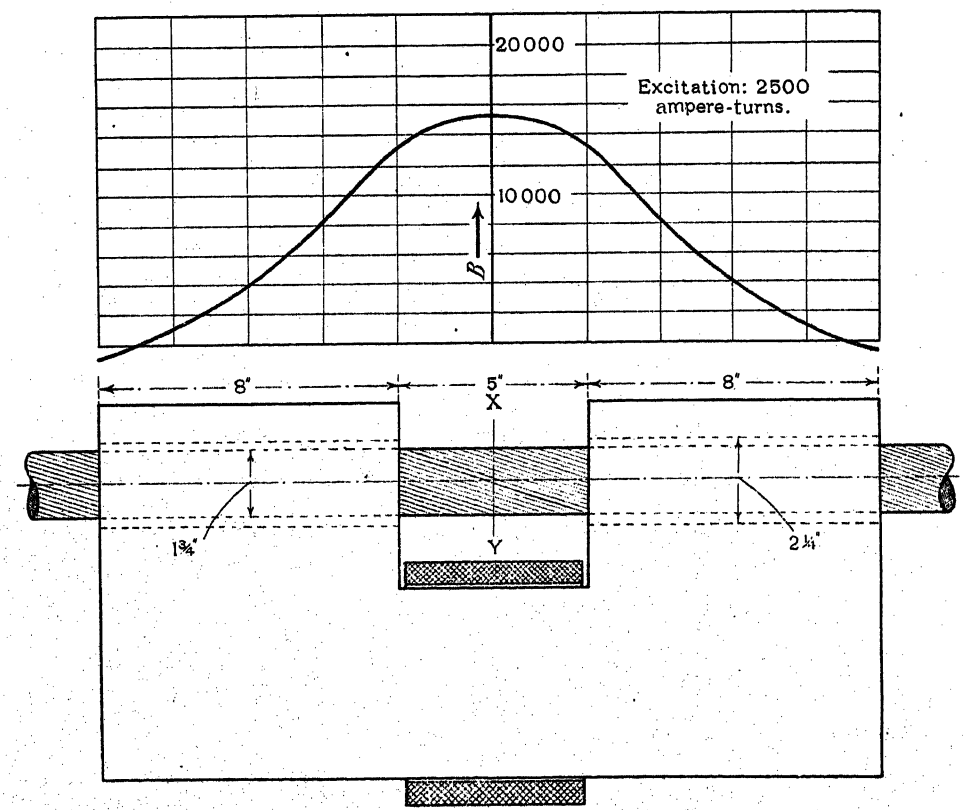


FIG. 1.—Magnetic circuit used in tests.

in the case of a composite structure such as a wire rope, and some test data were given showing the relationship between the total flux which was developed in a locked-coil type of rope and the excitation ampere-turns for an excitation frequency of 25 cycles and 50 cycles per second respectively, a comparison also being made with the total flux obtainable when d.c. excitation was used.

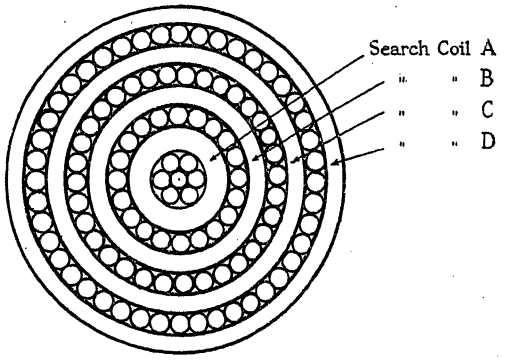


FIG. 2.—Cross-sectional view of completed sample, showing position of search coils.

All these tests were made with samples of rope as actually supplied for colliery winders, and the flux was measured by means of a search coil wrapped round that part of the rope in which the maximum flux density was developed. The flux measurements so obtained showed that, as compared with d.c. excitation, there was a distinct

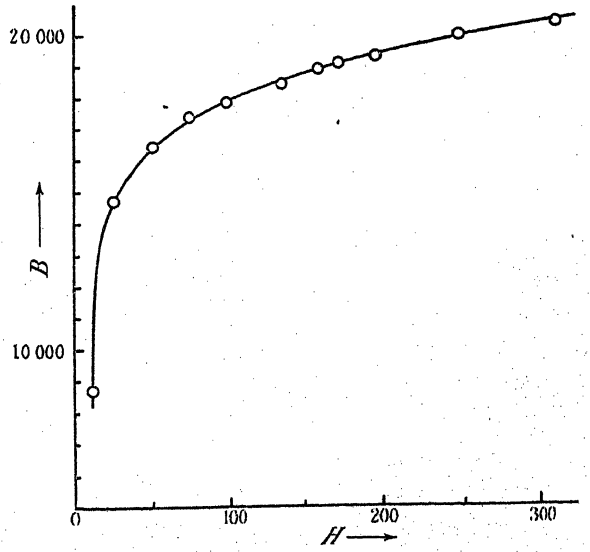


FIG. 3.—Magnetization curve of iron wire used in sample tested.

reduction of the total flux in a locked-coil rope unless the supply frequency was kept low. This reduction was most marked when the flux density was well below saturation value.

Now the information given by tests on a search coil which is linked with the whole cross-section of the rope does not enable any definite knowledge to be obtained as to how the total flux is distributed over the cross-sectional area. It is, however, of great practical importance to know something of the way in which the flux is distributed within the rope. In particular, such information is of considerable value in ascertaining whether there is any effect associated with a flaw which is characteristic of its depth. If such an effect can be found it will form the basis of a means for estimating the depth of a flaw in a locked-coil rope.

Whilst the mathematical theory of the screening effect of eddy currents has been worked out in full detail for thin laminated plates, the case of iron wires is a somewhat different problem and the screening effect of eddy currents in a compound structure like a locked-coil rope is a very intricate problem. It therefore appears hopeless to expect any generally useful practical assistance from a mathematical treatment. The problem is further complicated in the case of the electromagnetic testing

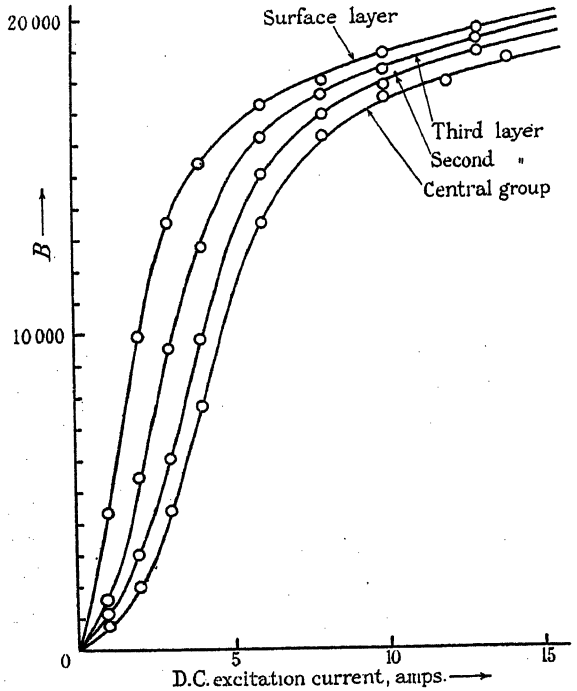


FIG. 4.—Ballistic tests.

apparatus under consideration because the flux enters the rope over an extended length, thus producing a cumulative effect at that part of the rope which is situated between the projecting poles (see Fig. 1).

The information which is required is a knowledge of the flux density in *each layer* of the rope as a function of the excitation ampere-turns. It is, of course, not possible to measure this flux density directly in an actual winding rope, as such a measurement requires embedded search coils embracing each layer. Some definite information as to the nature of the flux distribution over the cross-section of a locked-coil type of rope is, however, of such great importance in obtaining a complete knowledge of the action of the rope-testing apparatus that it has been considered desirable to build up a sample with embedded search-coils and to examine the flux distribution by means of ballistic tests and tests with alternating-current excitation at various frequencies.

The Experimental Sample with Embedded Search-Coils.

The experimental sample was made to be as nearly as possible an exact replica of a locked-coil type of wire rope, the layers of the experimental sample being not quite so close together as in the locked-coil rope, owing to the built-in search coils. The effects disclosed by the tests on the experimental sample must therefore be of the same nature as those which will occur in an actual locked-coil type of rope.

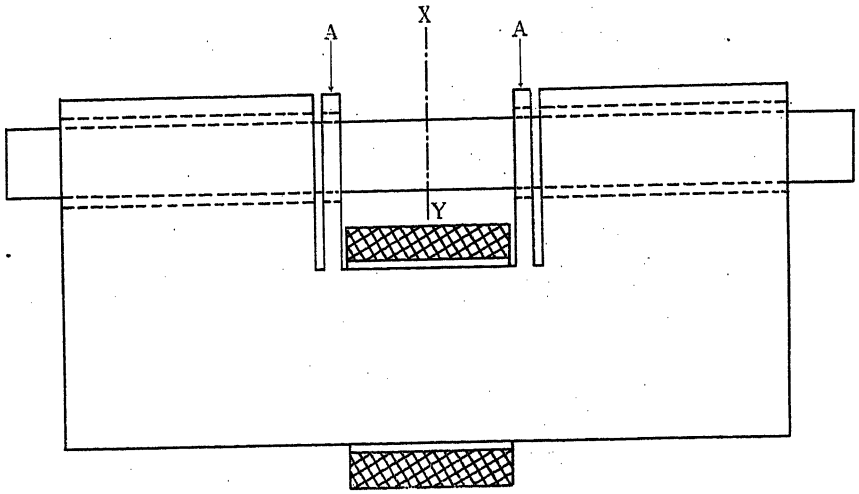


Fig. 5.

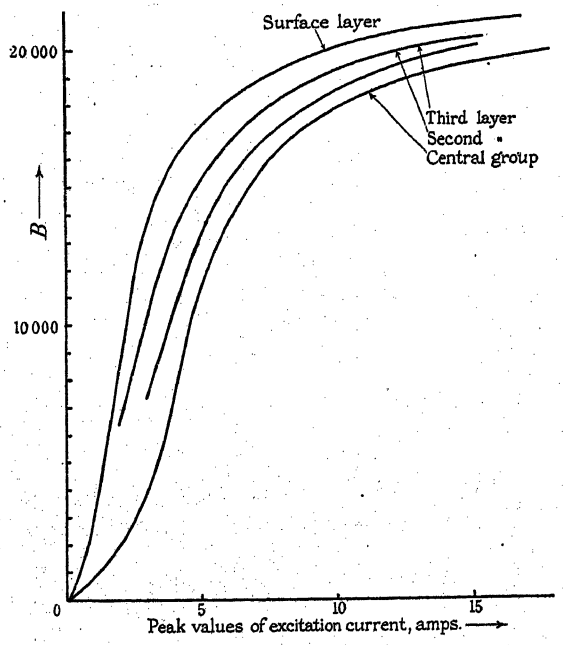


Fig. 6.—Excitation with alternating current at 18 cycles per sec.

Straight, mild-steel wire rods of $\frac{1}{8}$ in. diameter were used for this sample, each rod being coated with insulating enamel before assembly. A cross-sectional view of the completed sample is shown in Fig. 2. A first layer or central group of 7 wires was formed and a search coil (coil A) of 200 turns arranged to embrace this group. A second layer comprising 20 wires was then built up and a search coil (coil B) of 200 turns was wound embracing this layer. A third layer of 33 wires was then formed and a search coil (coil C) was wound on this layer. Finally a fourth layer of 44 wires was built up and the search coil D of 200 turns was wrapped on this surface layer. All these search coils were so arranged that their planes were all coincident and at right angles to the axis of the sample. The data of the area of the wires in each layer and also the mean area embraced by the respective search coils are as follows:—

First Layer or Central Group:
Area of iron wire = 0·57 cm^2
Mean area of search coil A = 1·55 cm^2

Second Layer:
Area of iron wire = 1·63 cm^2
Mean area of search coil B = 5·8 cm^2

Third Layer:
Area of iron wire = 2·69 cm^2
Mean area of search coil C = 12·4 cm^2

Fourth or Surface Layer:
Area of iron wire = 3·58 cm^2
Mean area of search coil D = 21·9 cm^2

The total cross-sectional area of the rope is thus 8·47 cm^2.

The general arrangement will be clear by reference to Fig. 2.

By connecting consecutive search coils in opposition in pairs, it is possible to measure the magnitude of the flux associated with each layer. By using search coil A alone the magnitude of the flux in the central group of wires is measured, and measurements with search coil D give the total flux through the sample.

In order to obtain the correct values of the flux density in the iron wires when the excitation is in the neighbourhood of saturation value, it is necessary to subtract from the measurement of the total flux that amount

which passes through the air space embraced by the respective search coils, and for this purpose it is necessary to know the magnetization curve of the iron wire of which the sample is built up. This curve has been obtained by arranging a group of the wires in a long standard solenoid and obtaining the B–H curve in the usual manner. The curve so obtained is given in Fig. 3.

(2) The Flux Distribution when D.C. Excitation is Used.

Tests made with d.c. excitation of the magnet system are useful as giving a standard of reference, since no such phenomenon as "skin effect" develops under these conditions. These tests were made with a Campbell high-sensitivity ballistic galvanometer, and the relationship between the excitation current and the flux density in the respective layers of the sample is given by the curves in Fig. 4.

The first noteworthy feature of these curves is that for a given value of the exciting current the flux density in each layer is different, being a minimum in the central group of wires and a maximum in the surface layer. Another important feature is that the shape in the neighbourhood of the origin is different for each curve. Both of these distinctive features are of great importance in considering the performance when a.c. excitation is used.

It is not at first obvious what the full explanation of these characteristic features of each layer of iron wires may be. Undoubtedly the main cause of the effects can be referred to the fact that the air-gap between the respective layers and the tunnelled holes in the magnet limbs is different for each layer, i.e. the air-gap associated with the central group is very much greater than that associated with the surface layer.

There is, however, another question which arises here, and that is whether the flux which enters the sample from, say, each band of 1 cm width of the surface of the tunnelled holes in the magnet limbs is distributed amongst the respective layers in the same proportion. Alternatively, does the flux which enters the sample from that part of the surface of the tunnelled hole which is near the inner flank of the magnet limb confine itself more particularly to any special layer? The answer to this question is of great importance and contains the clue to a method for examining the behaviour of each layer of an actual rope in practice, in which case, of course, it is not possible to make use of embedded search-coils.

A consideration of the results given in Fig. 4 suggests that the flux associated with the surface layer is more particularly the flux which passes through the inner slices, such as A, A, of the magnetic limbs as shown in Fig. 5, whilst the flux which is associated more particularly with the central group of wires passes across the air-gap further back towards the left-hand portion of the left-hand limb and the right-hand portion of the right-hand limb of the magnet system shown in Fig. 5. General considerations of symmetry also lead to the same conclusion as regards the magnetic circuits of the flux in the respective layers of a locked-coil rope.

The practical importance of this result is that it suggests a means for obtaining access to a flux band which is particularly associated with any one layer of the rope.

(3) Tests with A.C. Excitation at a Frequency of 18 Cycles per Second.

The frequency of the a.c. excitation for these tests was chosen sufficiently low to ensure that the skin effect would be small. In order to obtain the curves showing the relationship between the flux density in the respective layers and the excitation current, measurements were made of the induced e.m.f. in the search coils as follows: Coil A for the central group, coils A and B in opposition for the second layer, coils B and C in opposition for the third layer, coils C and D in opposition for the surface layer. By measuring the induced e.m.f. in coil D alone it is possible to determine the total flux through the sample; this gives a check on the measurements of the flux for the individual layers.

In order to deduce the magnitude of the flux from

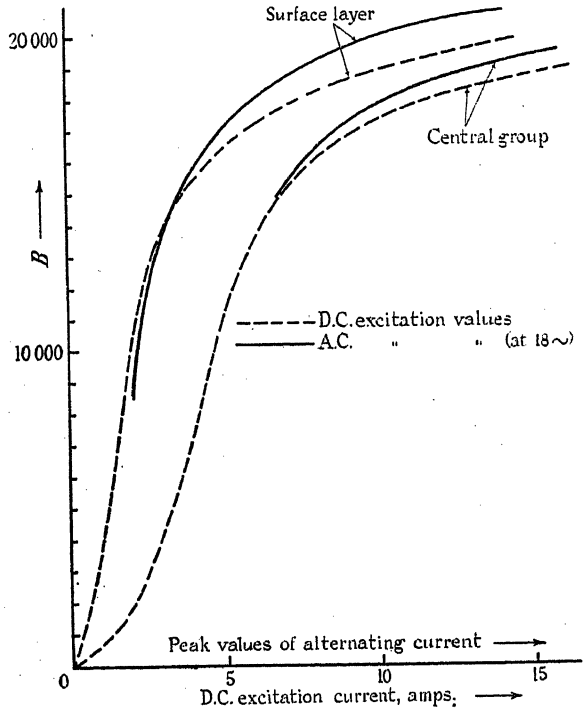


Fig. 7.

the R.M.S. value of the induced e.m.f., it is necessary to obtain the form factor of the e.m.f. wave. For this purpose an oscillogram of the e.m.f. wave was taken in each case and the form factor was then found graphically. From a knowledge of the R.M.S. value of the induced e.m.f. and the corresponding value of the form factor of the e.m.f. wave the maximum value of the total flux linked by any of the search coil combinations detailed in the previous paragraph was obtained. For values of the exciting current corresponding to saturation, correction was made for the flux in the air space which was linked by the search-coil combination, and in this way the flux densities in each layer was arrived at as a function of the exciting amperes.

In Fig. 6 the flux-density curves so obtained have been plotted with the peak values of the exciting current as abscissæ, and in this way a direct comparison can be

made with the corresponding curves given in Fig. 4 for d.c. excitation.

A comparison of the curves given in Figs. 4 and 6 shows that there is very little screening effect due to eddy currents and that the penetration is nearly as complete with a.c. excitation at a frequency of 18 cycles per sec. as with d.c. excitation. There is, however, one very prominent feature revealed by this comparison, viz. for the higher values of the exciting current the curve for a.c. excitation for any one layer lies distinctly above the corresponding curve for d.c. excitation. This effect is prominently seen in Fig. 7 in which the curves for the surface layer and for the central group are reproduced, the broken-line curves being the d.c. excitation values and the full-line curves the results obtained by means of a.c. excitation at a frequency of 18 cycles per sec. This implies that for high values of the excitation, the permeability of the iron rods is greater for a.c. than for d.c. excitation. This effect may be, at least in part, explained in the light of Ewing's experiments, in which he showed that when an alternating flux was superimposed on a magnetic specimen in such a way that this flux did not link the search coil, the hysteresis loop collapsed and the inward bend of the magnetization curve in the neighbourhood of the origin practically disappeared.*

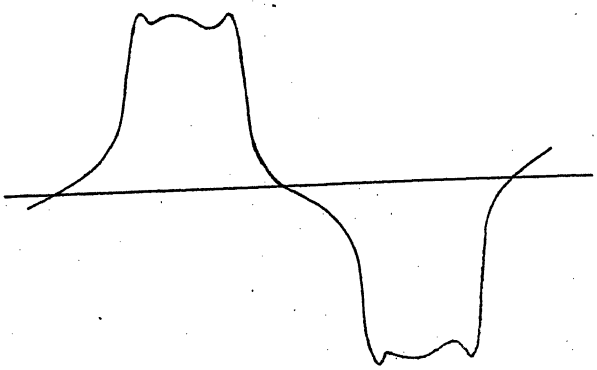


FIG. 8(*a*).—E.M.F. induced in search coil A, i.e. the e.m.f. due to flux in central group of wires.

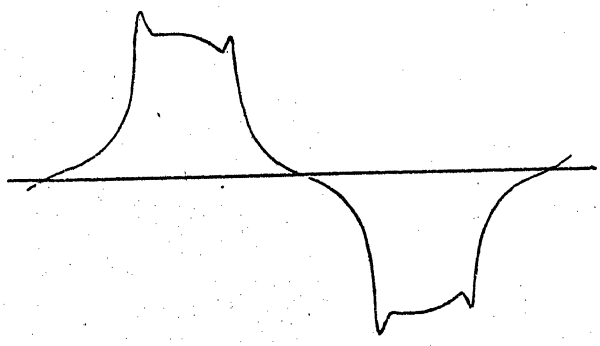


FIG. 8(*b*).—E.M.F. induced in search coils A and B in opposition, i.e. the e.m.f. due to flux in second layer of wires.

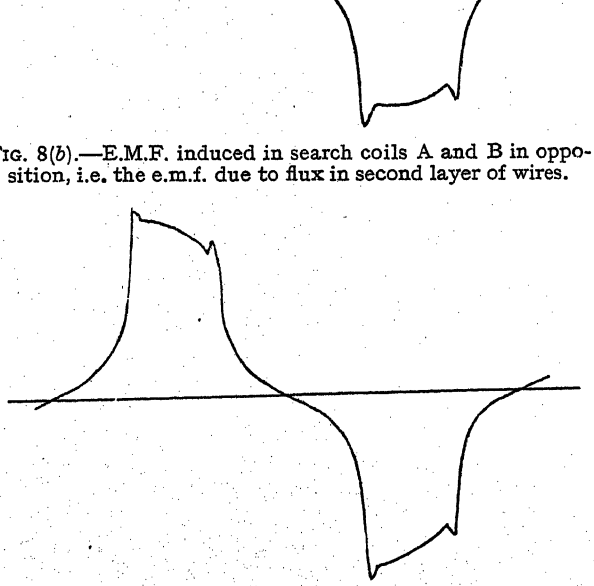


FIG. 8(*c*).—E.M.F. induced in search coils B and C in opposition, i.e. e.m.f. due to flux in third layer of wires.

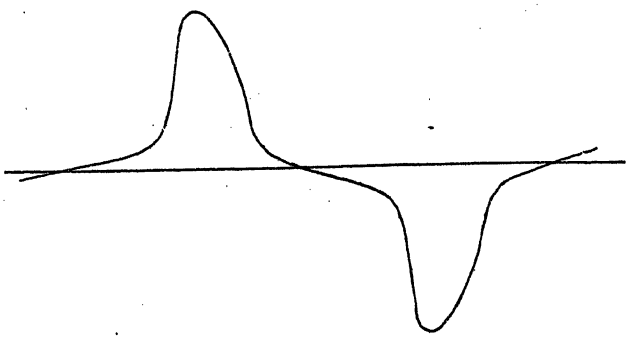


FIG. 8(*d*).—E.M.F. induced in search coils C and D in opposition, i.e. e.m.f. due to flux in surface layer.

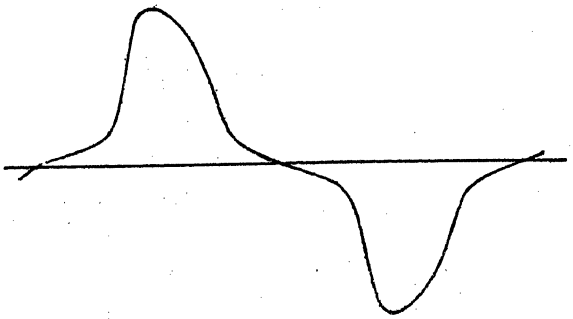


FIG. 8(*e*).—E.M.F. induced in search coil D, i.e. the e.m.f. due to total flux in rope sample.

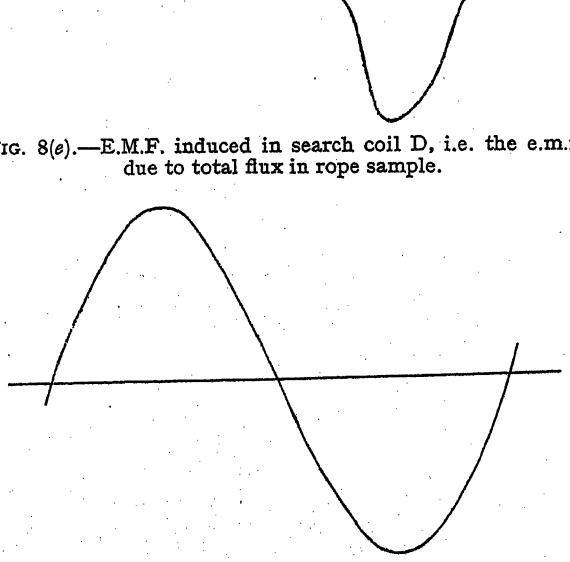


FIG. 9.—Wave-form of current in exciting coil of electromagnet.
Exciting current = 5·4 amps.
Supply frequency = 50 cycles per sec.

N. W. McLachlan† has shown that when the

* See also C. P. STEINMETZ: "Theory and Calculation of Electric Circuits."
† *Journal I.E.E.*, 1915, vol. 53, p. 818.

magnetization is produced by an alternating current of sine-wave form the permeability is greater than the permeability obtained when the magnetization is produced by a steady direct current.

(4) Tests with A.C. Excitation at a Frequency of 50 Cycles per Second.

A series of tests were also made with a.c. excitation at 50 cycles per sec. and the corresponding curves for the

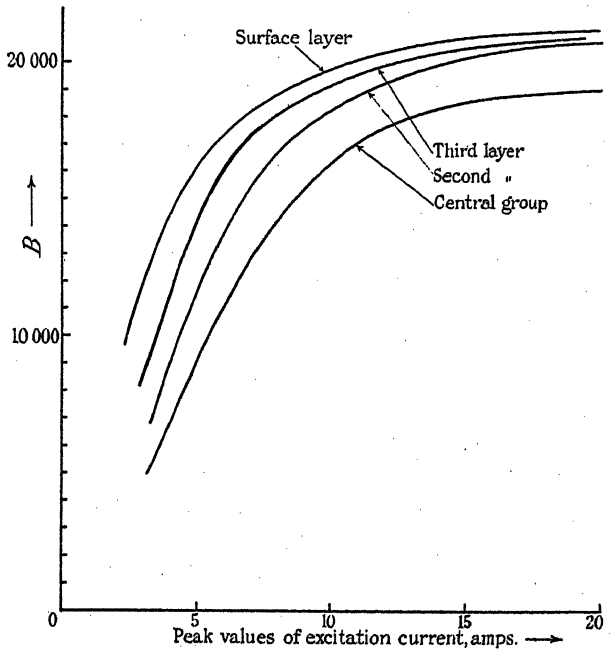


Fig. 10.—Excitation with alternating current at 50 cycles per sec.

several layers were obtained in the manner explained in Section (3). These curves are given in Fig. 10.

The difference between the wave-forms of the induced e.m.f.'s in the several layers is very striking. A representative set of oscillograms is given in Fig. 8, in which is also included the oscillogram obtained from the search coil D embracing the whole sample and thus giving a compound effect of the wave-forms of the fluxes in all the layers. These oscillograms were all taken with an excitation current of 10 amperes (R.M.S.).

An inspection of the wave-forms given in Fig. 8 shows that associated with each layer is a characteristic wave-form and that the wave-form given by the surface layer, for example, is widely different from that given by the central group.

In Fig. 9 is shown a typical oscillogram for the current wave; this is seen to be very nearly sinusoidal.

In Fig. 11 are reproduced, for purposes of comparison, the curves for the surface layer and the central group as given in Fig. 10. Also in Fig. 11 the corresponding curves for d.c. excitation are shown by broken lines. It is now apparent that there is a marked screening

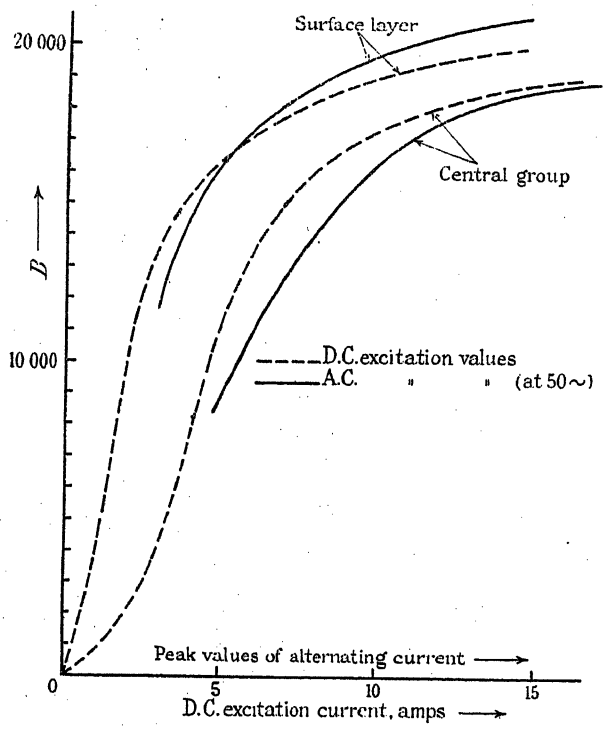


Fig. 11.

effect on the central group due to eddy currents at this frequency of excitation, the a.c. curve lying below the d.c. curve throughout the whole range of the excitation. For the surface layer, however, whilst the a.c. curve lies below the d.c. curve for the lower values of the excitation, the same effect as that noticed with 18-cycle excitation appears at the higher values of the excitation, that is, the a.c. curve lies above the d.c. curve. For the higher values of the excitation there will thus be two conflicting actions operating, viz. the tendency for the a.c. excitation to increase the effective permeability, and the tendency for the eddy currents to produce a skin effect and thus reduce the flux.

THE TECHNIQUE OF THE HIGH-SPEED CATHODE-RAY OSCILLOGRAPH.

By F. P. BURCH, B.A., and R. V. WHELPTON, M.Sc.

(*Paper first received 24th December*, 1931, *and in final form 5th April*, 1932.)

SUMMARY.

After an introduction in which the need for high-speed oscillography and the nature of the problems are explained, an equipment built for recording the "uncontrolled" surges of a 1 000 000-volt impulse generator is described. Attention is concentrated on the problems of discharge tubes, beam traps, sweep circuits, and screening. Examples of the oscillograms obtained are given.

(1) INTRODUCTION.

During the last 10 years electrical engineers have been forced to devote increasing attention to the momentary over-voltages to which their apparatus is subject. Such over-voltages arise from switching operations, the sudden development of faults, or, in the case of overhead transmission lines, from the inductive action of neighbouring lightning flashes, even in the absence of a direct hit. These disturbances are usually of extremely short duration—thousandths or even millionths of a second—but since the maximum voltage may be two, five, or even eight times normal they are often the determining factor in the design of the insulation. For example, when power is suddenly applied to one end of a cable or transmission line a wave of voltage travels along the line. On arrival at the far end this wave is doubled by reflection from the transformer or connected apparatus, and the whole of the double voltage is momentarily concentrated across the end-turns of the winding.

This fact has long been appreciated, and it has become the practice to reinforce the insulation of the end-turns, and sometimes to interpose a choke coil between the line and the transformer. But as a result of recent oscillographic researches it is now recognized that the concentration of voltage across the end-turns, lasting only a fraction of a millionth of a second, is not the whole story. The entire coil is "shocked" by the wave into an oscillation of somewhat complicated type which persists in general for some thousandths of a second, and imposes abnormal voltage gradients on the middle parts of the winding; and though these voltage gradients are not so great as the initial gradients at the end-turns, they may be equally dangerous because they last so much longer. For the longer the time of application, the lower is the voltage necessary to break down any insulator. These oscillations of the transformer winding are in some cases intensely aggravated by resonance between the line and the winding, and the use of a choke coil, instead of removing the danger to the transformer, may actually increase it.

From the foregoing example it will be realized that with the growth in the size of electrical undertakings, the insulation engineer is compelled to study in detail the mechanism of the production of transient over-voltages, their magnitude and duration, and the ability of insulation to withstand them, as well as the possibility of suppressing them by such devices as surge absorbers and lightning arrestors. A high-voltage laboratory must be equipped, firstly with an impulse generator to produce high-voltage transients, and secondly with a cathode-ray oscillograph capable of recording the variation of voltage with time in a single transient occupying less than a millionth of a second.

The small sealed glass oscillographs, using cathode voltages from a few hundred to a few thousand volts, which are to-day found in almost every electrotechnical laboratory, are admirably adapted to the study of *periodic* phenomena, even at frequencies of a million cycles or more, for a steady picture can be obtained on the screen by causing the cathode-ray spot to retrace continually in synchronism with the phenomenon under investigation. They do not, however, give sufficient intensity for the recording of a single transient lasting less than about 10^{-3} sec. For transients measured in microseconds (1 microsecond = 10^{-6} sec.) an instrument of a totally different type is necessary. The pioneer of high-speed single-transient recording was Dufour, who insisted on the necessity for a beam of high-voltage cathode rays, and took the important step of introducing the photographic plate into the vacuum. These expedients inevitably require a rather bulky apparatus with continuously running vacuum pumps.

The progress of cathode-ray oscillography up to and including the work of Dufour was described in a paper before the Institution by Prof. MacGregor-Morris and Mr. Mines in 1925.* Since that time high-speed instruments have been improved out of all recognition. German investigators have been chiefly responsible, notably Rogowski, who was the first to photograph travelling waves,† and has pushed the speed of recording very close to the limit imposed by the nature of cathode rays.‡

This paper is intended as a contribution to the technique of high-speed oscillography. The principal problems of high-speed recording are the following:—

(1) The problem of designing a discharge tube to provide a perfectly steady, intense beam of cathode rays.

(2) The choice of the method of obtaining a photographic imprint, i.e. whether the beam should fall directly on a film inside the vacuum, or should pass through a Lenard window on to a film outside the vacuum, or should strike a phosphorescent screen the light from which is recorded on a film outside the vacuum.

* See Bibliography, (1). † *Ibid.*, (2) and (3). ‡ *Ibid.*, (4).

(3) The problem of arranging that the beam shall be already moving over the film along the axis of time at the moment when the transient under investigation gives it a motion at right angles parallel to the voltage axis. This problem becomes especially difficult when the phenomenon under investigation is one of which the moment of occurrence cannot be controlled, e.g. a lightning disturbance. The earlier workers solved it by moving the beam continually backwards and forwards along the time axis, so that it was always ready to be deflected at right angles by the transient voltage. For certain very special problems this method is without peer, but the replotting of the records into ordinary graphs of voltage against time is a tedious matter. It has therefore become almost universal practice to sweep the beam once only across the film, so that an ordinary voltage/time graph is obtained directly. This single sweep must of course be initiated at the right moment, and therefore when the incidence of the transient is not under control it is necessary to arrange that the transient shall operate a relay which starts the time-sweep. Further, since even the swiftest relay has some time-lag, if the start of the transient is to be recorded it must first be brought to the relay, and then conveyed to the voltage deflection-plates of the oscillograph by an electrical line long enough to delay its arrival until after the relay has operated.

The methods adopted by different workers for solving these problems vary widely, and are in many cases ill-adapted to researches of a type other than that for which they were devised. The equipment described in this paper was built primarily for work with a 1 000 000-volt impulse generator.* For such work some American laboratories have so linked the impulse generator and oscillograph that the closing of a switch starts the time-sweep of the oscillograph, and immediately afterwards trips the impulse generator. This arrangement requires cumbersome and expensive high-voltage apparatus, and makes the oscillograph an integral part of the impulse testing equipment. The authors preferred to build an instrument capable of recording uncontrolled transients, and to treat even the artificial surges of the laboratory as "uncontrolled." This course provides an oscillograph which is cheaper and more convenient for impulse testing, as well as being applicable not only to a variety of laboratory problems but also to lightning and transmission-line investigations.

(2) General Features of Construction.

In general features the instrument is similar to those of Continental workers.† The authors adopted a vertical construction. Referring to Fig. 1, at the top is the discharge tube or source of cathode rays, which is here shown only diagrammatically, being described in detail later. From the discharge tube the rays pass through a 1-mm hole in the aluminium anode block into the main tube as a slightly divergent beam. The main tube is of drawn brass 17·8 cm bore and 145 cm long, supported in an angle-iron frame. Surrounding it about half-way down is the magnetic focusing coil, through which direct current is passed and adjusted so that the magnetic field causes the diverging beam of electrons to converge and come to a sharp point focus on the phosphorescent screen or photographic film. The focusing coil is shrouded with iron to confine its field. Inside the tube at the same height are diaphragms of aluminium backed with lead, so arranged as to limit the beam while allowing a free passage of air. Immediately below the focusing coil is a 4-pole electromagnet system by means of which the beam can be given independent steady deflections in two directions at right angles, and thus its zero position brought to any desired point on the photographic film. Inside the tube, below the position magnets, are the electrostatic deflection-plates. These are carried on a removable framework, and are inclined for maximum voltage sensitivity.

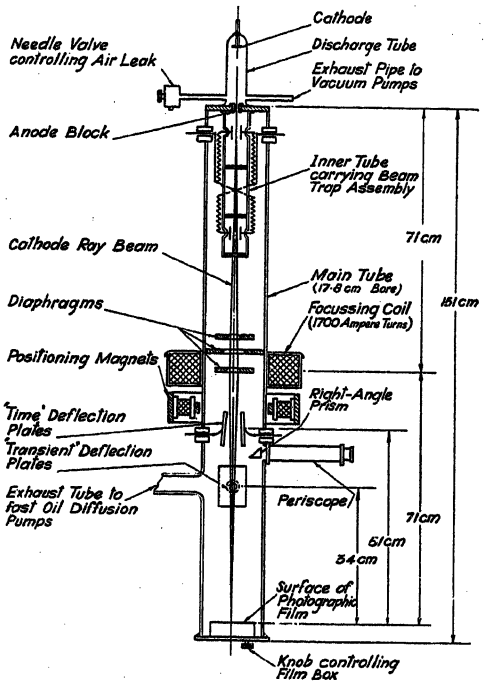


Fig. 1.—Diagrammatic sketch of cathode-ray oscillograph.

The upper pair is used for the time and the lower for the transient deflection. Contact is made to them by flat springs, from which leads are brought out through vacuum-tight insulating bushes. The photographic records are obtained by allowing the cathode-ray beam to fall on a film inside the vacuum; the film box is mounted on the lower cover-plate of the tube and accommodates standard 6 × 9 cm film on which 12 exposures of 6 × 6 cm are obtained. The film is normally covered by a lid coated on its upper surface with phosphorescent zinc sulphide. To open the lid, a shaft passing through a vacuum-tight cone joint is turned; turning in the opposite direction closes the lid and, if continued, winds on the film for the next exposure. The phosphorescent screen can be observed by means of a small telescope and right-angle prism.

In the upper half of the main tube, supported from the top cover-plate, is the beam-trap system, which is described later. The main tube is exhausted through a very short, wide pipe by two cascaded Metropolitan-

* See Bibliography, (5) and (6).
† See (for example) Bibliography, (7) and (8).

Vickers condensation pumps operating with " Apiezon " low-vapour-pressure oil. The very great speed of this pumping system (20 litres per second) enables it to maintain a vacuum of the order of 10^{-4} mm of mercury in the main tube, despite the continual leakage of gas from the discharge tube through the hole in the anode block. In the discharge tube a comparatively high gas pressure, 1 or 2 $\times$ 10^{-2} mm of mercury, is required for the production of the electron beam. Air is accordingly allowed to leak in continually through a needle valve and is removed by a separate oil condensation pump. In this way, by sweeping air through at a good rate, any bursts of gas which may be evolved from the walls of the discharge tube are quickly removed and thus momentary pressure-rises are avoided. The backing vacuum for all condensation pumps is provided by two cascaded pumps of the rotary vane type.

(3) Discharge Tubes.

These have been of the cold-cathode type exclusively, supplied through a series resistance from a rectifier set of which the maximum voltage is limited to 55 kV by the condensers available. The authors at first tried glass tubes 75 cm long, using the extra focusing coil and magnets, after Rogowski,* to bring the beam to a focus on the anode hole. The upper part of the tube was of 13 mm bore and 25 or 50 cm long, the remainder being of 25 mm bore. The cathode was a cylindrical aluminium rod 11 mm in diameter with a flat end, the sharp edge being rounded off. At first these tubes would run steadily for a few minutes only, after which sparking appeared near the cathode. This was soon found to be due to overheating. Oil cooling of the cathode, which appeared to receive about half the heat, made a great improvement, and the trouble was completely cured when a glass oil-jacket was added round the narrow part of the tube. Transformer oil, circulated by a small pump, was used. A sludge collected on the outer wall of the discharge tube near the cathode, but this did not appear to be detrimental; such tubes ran perfectly steadily for some hundreds of hours. A very high degree of polish on the cathode seemed to be unnecessary, and when flickering was observed this was always found to have been due to a leakage of grease through the cathode joint. To ensure perfect steadiness a series resistance of 1 megohm was found insufficient; a liquid resistance of at least 6 megohms was used. Silit resistance rods appeared to be satisfactory as long as there was no tendency to flicker, but when there was such a tendency they seemed to magnify it. The tube was run at about 1 mA, the voltage across it being 40 to 45 kV. At lower currents (0·6 mA) the cathode-ray beam began to become intermittent with a frequency of the order of 1 million cycles. A reduction of voltage increased the tendency to intermittence and reduced the frequency.

For the sake of compactness and simplicity, it is very convenient to use a metal discharge tube of the X-ray type and to dispense with the extra focusing coil. The authors accordingly tried a tube after the design of Messrs. Knoll, Knoblauch, and von Borries (see Fig. 2 of their paper).† But this tube would work for a few minutes only, after which a soft glow discharge broke out. The distance between the top of the metal anode tube and the cathode shoulder was increased or decreased, but without success; and no improvement was obtained by curving the Pyrex tube inwards into the space between the electrodes, or swelling it outwards away from the top of the anode tube. While these tubes were working, however, an excellent electron beam was obtained in all cases. It is probable, therefore, that the production of the beam is indeed wholly determined, as one expects and wishes, by the conditions inside the metal anode tube below the cathode face. The problem seems to be simply that of maintaining a sufficient creepage distance along the insulation, while at the same time restricting the space available for ionization in that neighbourhood. One solution, not, however, very simple to construct, has been given by Berger.* The authors were able to obtain a workable

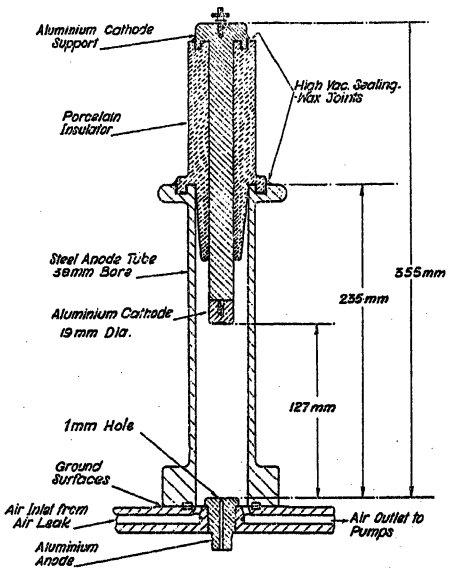


Fig. 2.—Metal discharge tube.

arrangement with the Knoll type tube by inserting below the cathode shoulder an insulated metal anchor-ring supported on a glass ring resting on the top of the anode tube. There were occasional flickers of green glow round the rings, but these did not appear to affect the current or the cathode-ray beam.† However, the very simple and robust design shown in Fig. 2 is completely successful. The distance from cathode to anode tube is now nowhere greater than at the cathode face, and the creepage distance along the porcelain insulator may be made as great as desired. This was suggested by Mr. J. M. Dodds, who gave great assistance in these experiments.

With these tubes oil-cooling of the cathode is unnecessary; water-cooling of the anode is desirable. With reasonably smooth surfaces, a slightly convex cathode gives as good results as a concave one, but if the central part (some 6 mm diameter) of the cathode face is dirty, or deeply scratched with a knife, the intensity of the beam is poor. Scratches on the sides do not matter.

* See Bibliography, (7). † *Ibid.*, (9).

* See Bibliography, (10).

† The authors' experiences with the Knoll type tube are confirmed by a recent paper of Dicks see Bibliography, (11)], who also adopted a floating electrode.

When the cathode is badly pitted, or if a small hole is drilled in it, the intensity of the beam is reduced.* A pointed cathode gave no beam at all. A truncated cone of 36° angle, terminating in a flat face 5 mm in diameter, seemed to give as good results as a concave cathode, but the current became unsteady above 2 mA. With these tubes the authors obtain a more intense beam than with the glass discharge tubes, but in addition to electrons the beam contains considerable numbers of atomic particles—the so-called "retrograde rays."† These, which were not appreciable with the glass discharge tubes, originate as negative ions, but can gain or lose charges in their passage through the gas. They thus pass as neutral particles through the charged beam trap, and reach the screen as a mixture of neutral atoms and positive ions. The deflections of the latter show that their energies approach those of the electrons; the former are distinguished from X-rays by the marked "fatigue" of the phosphorescent screen. To avoid undue fog the film must not be exposed to these particles for more than 5 minutes; they could of course be sifted out by giving to the electrons a magnetic deflection, by "filtering" the beam through a thin film of aluminium or Cellon, or by using the beam-trap arrangement of Norinder.‡

(4) Beam Trap.

In order to avoid fogging of the film, Dufour applied voltage to the cathode-ray tube only during the short time of photographing. This method has been developed and extensively applied by American investigators.§ The method used by Continental workers is, however, much to be preferred: the discharge tube is continually excited, and the beam is prevented from entering the lower part of the deflection tube by a trap from which it is released when required. In Norinder's ingenious trap system the transient voltage itself deflects the beam past a target which normally intercepts it; and where an oscillatory time-base is to be used this has many advantages. But with the single time-sweeping movement now almost universally employed it is best, especially for high-speed work, to release the beam by removing an artificially applied voltage which normally deflects it away from a central hole. The authors first tried to build a beam trap for use with a "Kipp" relay of the type devised by Gábor.‖ With a beam of appreciable angular divergence, however, the design of a low-voltage trap is difficult,¶ while if a high-voltage jump is required the design of a quick-acting "Kipp" relay is equally difficult. Having failed to produce satisfactory trapping at 300 volts, the authors decided to use a spark relay and a high-voltage trap. The latter has two stages, the plates being cross-connected to give zero deflection for a small voltage (Gábor). These connections are made by resistances, from the mid-points of which the external connections are taken. The pairs of plates are thereby prevented from oscillating "against each other" when the beam-trap is discharged. The plates of each pair are 19 × 50 mm, and are 19 mm apart. Measuring from the bottom of the anode we have at 5·9 cm the centre of the first pair, at 16·2 cm a diaphragm of aperture 3·6 mm, at 31·5 cm another diaphragm of 6·3 mm, at 37 cm the centre of the second pair, at 51 cm an 8-mm diaphragm, and at 70 cm the limiting diaphragm (6 mm). The trapping of electrons is believed to be absolutely complete at 1 500 volts.

(5) Time-Sweeping Circuits.

It was decided from the outset that the spark which released the beam from its trap and initiated the time-sweeping movement should be tripped automatically by the impulse under investigation, and not vice versa. The sweeping movement is of course obtained by the discharge of a condenser through a resistance or a saturated valve. In making their choice from the great variety of possible arrangements the authors were guided by the following considerations:—

(1) The circuit must be tripped by a conductively conveyed impulse of either polarity, as quickly as possible. The voltage and quantity of electricity necessary in the impulse should be as small as possible.

(2) It is most important that the time scale should not be distorted by currents flowing in the leads which convey the tripping impulse. Such distortion may arise either through inductive coupling of the trip and sweep circuits, or through impedance or a spark-gap common to both.

(3) For some kinds of work, tripping must occur even with quite a slow voltage-rise. In this case also the charge required should be small, and preferably should not alter the potentials of the sweep-plates before tripping.

(4) In high-speed work it is desirable that the sweep deflection-plates should be equally and oppositely charged with respect to the earthed metal tube of the oscillograph, otherwise the focus of a beam of large angular divergence is impaired.

(5) For the same reason the common potential of the beam-trap plates during the exposure should be that of earth.

(6) The spot must be prevented from retracing slowly over the film when the condensers recharge after the exposure.

In order to obtain amphipolar tripping the impulse must be made to affect the voltages across two spark-gaps simultaneously and in opposite senses. There are two types of circuit arrangement, according to whether the gaps are in series (Fig. 3*a*) or in parallel (Figs. 3*b*, 3*c*) with respect to the impulse leads. In these diagrams the various poles of the spark-gaps are supposed to be given the indicated initial voltages by connection through very high resistances to sources of the required potentials. The circuits as shown are suitable for a tripping impulse taking the form of a variation of the potential of a single wire with respect to earth. Such arrangements are the most generally useful; in special cases where the electrification of the trip circuit is initially symmetrical and must be maintained so at every instant of time, the symmetrical analogue of Fig. 3*c* or, better, that of Fig. 3*b*, must be employed. In these circuits the two spark-gaps are separated.

* In this connection see Rühlemann [Bibliography, (12)].
† See Bibliography, (13).
‡ *Ibid.*, (14).
§ See, for example, Bibliography, (15, 16, and 17).
‖ See Bibliography, (18).
¶ For this purpose Boekels [see Bibliography, (19)] puts one pair of plates above the 1-mm diaphragm, i.e. effectively in the discharge tube.

The series arrangement, Fig. 3(*a*), is distinguished by the fact that only one spark-gap responds, but it has the great disadvantage that during the passage of the spark the currents in the impulse lead flow to earth not only through the idle resistance and the spark-gap, but also through the sweep condenser C. The latter circumstance, in particular, not only introduces a small capacitative coupling between the sweep and trip circuits, but also makes it difficult to avoid a considerable magnetic coupling. Further, the sensitivity is low, since only half of the impulse voltage is applied to a gap carrying the full sweep voltage, and the impulse has to charge up the stray capacitance to earth of the condenser. In addition, when the gap XY responds requirement (5) is not satisfied.

When the gaps are in parallel with respect to the impulse lead the response of either gap throws overvoltage on the other, which therefore breaks down immediately afterwards. There are three possibilities, according to whether the sweep current flows through the gap which short-circuits the impulse, or the other, or both in series. The second alternative (Fig. 3*b* with the impulse applied to sphere X) has the advantage of giving very complete decoupling. The sensitivity is fair: the impulse has to charge up the stray capacitance of the auxiliary condenser C′; the full impulse voltage is applied to XY, but YZ receives a fraction $R/(R + r)$ only. Each gap carries a voltage equal to the sweep

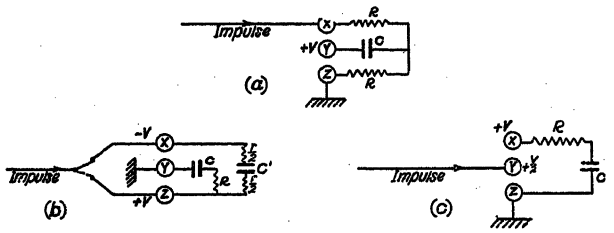


FIG. 3.—Amphipolar trip circuits.

voltage. The resistances $r/2$ must be included, to prevent oscillatory discharge of C′. When the sweep current flows through both gaps we have the familiar circuit of Fig. 3(*c*) in which the impulse current passes through one of the gaps. The full impulse is now applied to gaps carrying only half the sweep voltage. The stray capacitance to be charged is very small, and there is no shunting impedance, so that a steep-fronted impulse having a " tail " a few metres long will be doubled by reflection.

For a slow voltage-rise Fig. 3(*c*) is obviously the most suitable, and the authors accordingly adopted it. The importance of a symmetrical electrification of the sweep-plates was forced on them by preliminary experiments; with a beam of angular diameter 0·027 radian, a deflection of 2 cm, one sweep-plate being earthed, converted a fine spot into a patch several millimetres in diameter. Fig. 7 shows the effect with the beam stopped down to 0·009 radian; one plate was earthed and the potential of the other varied from zero at the beginning to 3·5 kV at the end of the record. In Figs. 8, 9, and 10 the sweep-plates were symmetrically electrified, with the result that the focus remained unimpaired by the sweep deflection. As regards the transient deflection, in electrotechnical work, of course, one usually wishes to work with one plate earthed, and all the authors' photographs have been taken in this way. That this does not give rise to appreciable loss of focus in their instrument is probably due to the fact that the transient deflection plates are closer together than the sweep-plates, and therefore the end-effects are less important.

Symmetrical electrification of the sweep-plates is not easily arranged if the condenser discharges through a valve, and therefore the authors preferred to use resistances. The complete sweep circuit, with which the oscillograms of Figs. 8, 9, and 10 were obtained, is

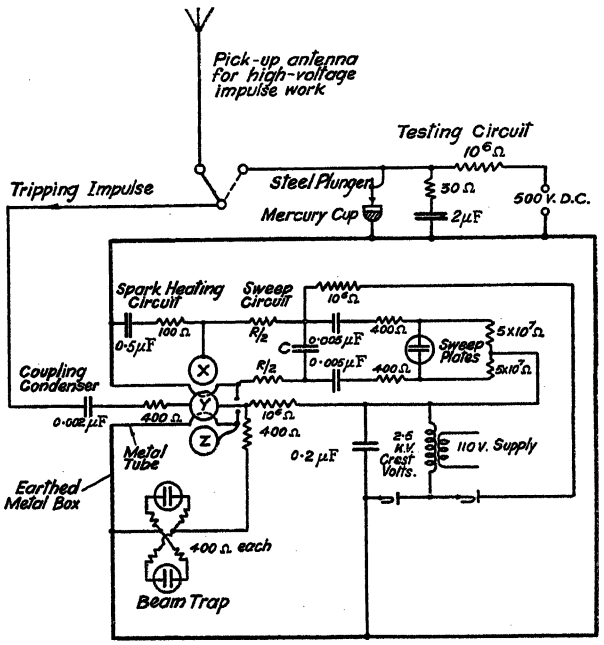


FIG. 4.—Complete sweep circuit.

shown in Fig. 4. As in Fig. 3(*c*), one pole Z of the gap is directly earthed; this is not essential, but was done to ensure the satisfaction of requirement (5). When the sparks occur, the common potential of the sweep-plates, which was previously 2·5 kV, jumps to zero. At the end of the exposure the plates have potentials + and − 2·5 kV. This plan makes it possible to arrange that the final position of the spot shall be a long way off the film, that is the time scale nearly linear, without the use of powerful opposed electric and magnetic deflections, which, the authors found, slightly impaired the definition at the beginning, even with symmetrical electrification.

The resistances in the sweep and beam-trap circuits must of course have such values that the discharge of these circuits is non-oscillatory. When this is the case, distortion of the time-scale can only arise from oscillatory currents flowing in the trip circuit. When the e.m.f. which provides the tripping impulse is non-oscillatory, only free oscillations are possible, and these can be prevented by including in the trip lead, close to the middle sphere, a resistance equal to the surge impedance of the lead. In practice, however, the tripping e.m.f. is often itself oscillatory, and, moreover, several

times stronger than is strictly necessary; and forced oscillations of course cannot be wholly suppressed. Since the oscillatory currents are superimposed on the sweep-current through one of the spark-gaps, they may, if of large amplitude, momentarily reduce the current through it to zero. The resistance of the spark then rises, and does not again become low until an appreciable quantity of electricity has passed. To guard against this, the well-known device is employed of passing through the spark-gaps, in addition to the sweep current, a large unidirectional heating current from an auxiliary condenser and resistance. But fluctuations in the resistances of the sparks seem to be less important as sources of time-scale distortion than inductive coupling between the trip and sweep, or trip and beam-trap circuits, and the authors were unable to obtain undistorted oscillograms until they took special precautions to reduce these mutual inductances. They could, of course, theoretically be made zero by a suitable disposition, but the authors preferred simply to make them very small by constructing the spark-gap as shown.

There is one case in which, although the tripping e.m.f. is non-oscillatory and of moderate magnitude, the suppression of free oscillations in the trip circuit is quite indispensable. This is when the impulse is conductively derived from a spark-gap, e.g. the 500-volt testing spark shown in Fig. 4. If resistance is omitted the current builds up, by repeated reflections at the ends of the trip line, to a very large amplitude, and then executes protracted quasi-stationary oscillations at the frequency determined by the capacitance of the coupling condenser and the whole inductance of the trip circuit.

Requirement (6)—no retracing—can be fulfilled in various ways. One of the simplest is to connect the sweep-plates across the resistance instead of the condenser.* This, however, is undesirable, since it immediately introduces into the time-scale any momentary fluctuations of the sweep current. Rogowski† uses a relay mechanism which retraps the beam by magnetic deflection. One way of dispensing with a relay, which the authors have used successfully, consists in connecting the beam trap across the spheres XZ; and using a rather small spark-heating condenser ($0{\cdot}05\,\mu$F.). With suitable resistances one can then arrange that the sparks go out when the potentials of the condensers have fallen to a value—say 2 000 volts—which is still sufficient to operate the beam trap. The authors prefer, however, the method shown in Fig. 4. The beam trap is connected across the spheres YZ, and when the sparks go out it recharges before the potentials of the sweep-plates have changed appreciably.‡

Much has been written about the time-lags of spark-gaps in responding to sudden applications of voltage, and the effect thereon of surface contamination. It has been stated§ that a sphere-gap freshly polished with clean carborundum paper will respond within less than 10^{-8} sec., even in the absence of ionizing radiations. The authors have not been able to obtain reliable results with this or any polishing method alone, but they obtain satisfactory results by the well-known device of irradiating the gaps with a quartz mercury lamp, when this is placed a few inches away. Response occurs regularly to a 500-volt impulse of either polarity with a time-lag which very seldom exceeds $0{\cdot}2$ microsecond. Some hundreds of sparks can take place before any adjustment is necessary. In high-voltage impulse work the tripping impulse is picked up by a small antenna. For testing purposes and for low-voltage experiments, the trip lead is connected to a steel rod and also through

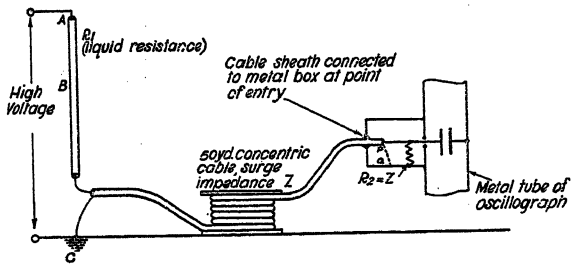


FIG. 5.—Resistance potential divider and screening arrangements.

a high resistance to a 500-volt supply. Plunging the rod into an earthed mercury cup then provides the tripping impulse, and may also simultaneously initiate a 500-volt transient in any desired apparatus connected between the rod and the mercury. The arrangement is shown in Fig. 4; it will be seen that a " heating " current is provided for the spark at the mercury cup.

(6) POTENTIAL DIVIDER.

The measurement of high-voltage transients of course requires a potential divider to tap off a few hundred volts

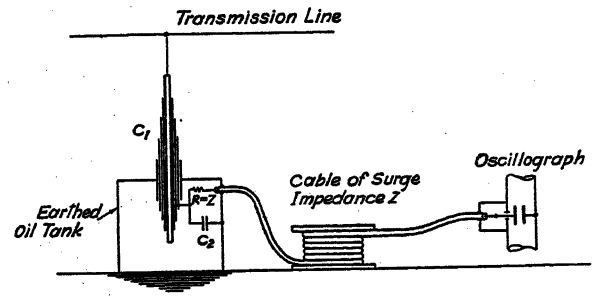


FIG. 6.—Simple potential divider for transmission-line recording.

for the oscillograph. Following Gábor, the authors connect the potential divider to the oscillograph by a rubber-insulated concentric cable which is long enough (50 or 60 yards) to delay the arrival of the impulse at the deflection plates until after the sweep circuit has tripped, thereby ensuring that the start of the impulse is recorded. For high-speed work with laboratory impulse generators, a resistance potential divider is usually satisfactory; but where the transient is superimposed on a power voltage, as in transmission-line work, condensers must be included. Fig. 5 shows Gábor's circuit for a resistance potential divider, while Fig. 6

* See Bibliography, (20). † *Ibid.*, (21).

‡ Boekels [see Bibliography, (19)] has also arrived at this principle. The modification which he adds to it in his Fig. 13 would be applicable even if the circuit contained only one spark-gap, and so represents yet another method, and he describes still another, due to Rogowski, in which the beam retraps itself by an arrangement of Faraday cylinders.

§ See Bibliography, (22).

shows the simplest arrangement for transmission-line recording. The division of voltage is effected by two capacitances C_1 and C_2 in series. C_1 may be a condenser bushing; C_2 is a low-voltage condenser having a very much greater capacitance than the delay cable. For transmission-line work at the highest speeds resistances and condensers must be used in combination; such an arrangement was given by Gábor. Improved potential-divider circuits have been discussed elsewhere.*

(7) Screening.

Since the oscillograph is situated only 6 yards from the impulse generator, very effective screening has been necessary. Indeed, the induced e.m.f.'s were at first so strong as not merely to distort the oscillograms hopelessly but even to break down the insulation of parts of the apparatus. The circuits have been enclosed in boxes of $\frac{1}{16}$ in. sheet steel, whereby also the magnetic fields of the control resistances are prevented from affecting the beam. A point in connection with the screening of the voltage-deflection circuit is worthy of special mention. Referring to Fig. 5, when the high-voltage applied to the potential divider, that is, the line integral of electric force down ABC, rises from zero and fluctuates in any manner, a wave enters the cable, establishing a potential difference between core and sheath which is a correct small-scale reproduction of these fluctuations. Independently of this, a wave also travels along the outside of the cable sheath; one may say loosely that both core and sheath together are raised in voltage by the fluctuating magnetic fields in the region between the cable and earth. If the deflection plates (and the resistance which shunts them in the circuit of Fig. 5) had no capacitance to earth, the currents flowing on the outside of the cable sheath would be of no consequence; it would be sufficient simply to connect the deflection plates and shunting resistance across the cable without any "earthing" of the sheath at the oscillograph or other special precautions. Actually, however, each deflection plate has capacitance to the metal tube of the oscillograph comparable with the capacitance between the two plates. In order to ensure that the voltage between the plates is determined only by the wave of voltage between core and sheath which is applied at the input end, it is therefore necessary that the cable sheath should in effect be made an integral part of the metal tube of the oscillograph, core and deflection plates forming a screened system, as shown in Fig. 5. How essential it is that this should be properly done is shown by the fact that it was found to be unsatisfactory to bring the sheath of the cable into the metal box in an insulated manner and then connect it to the box by a wire PQ a few inches long. This procedure introduced quite large spurious e.m.f.'s. So long as the screening is properly carried out, it is in practice immaterial whether or not the tube of the oscillograph is "earthed" directly, as well as through the cable sheath; such an extra "earth" cannot affect the correctness with which the line integral of force down ABC is measured, though it will, no doubt, slightly affect this line integral itself.

To check the efficacy of the screening the authors carried out various tests, notably one in which R_1 was disconnected from the cable and earthed, and the sheath of the cable at the potential-divider end was connected to the core and metallically sealed over it and also earthed. With a cable in which the sheath consisted of an open-mesh braiding, small residual e.m.f.'s

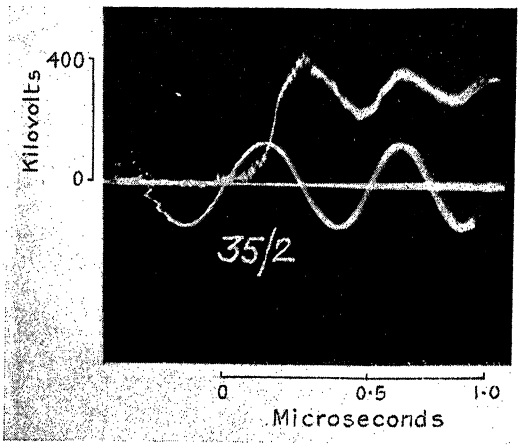


Fig. 7.—Impulse wave with oscillations. Loss of focus due to asymmetrical deflecting field.

remained, but these disappeared when lead-covered cable was substituted.

It is of interest to note that the authors were able to take undistorted oscillograms of the open-circuit wave of the impulse generator before the high-voltage circuit supplying the cathode was screened at all. No doubt

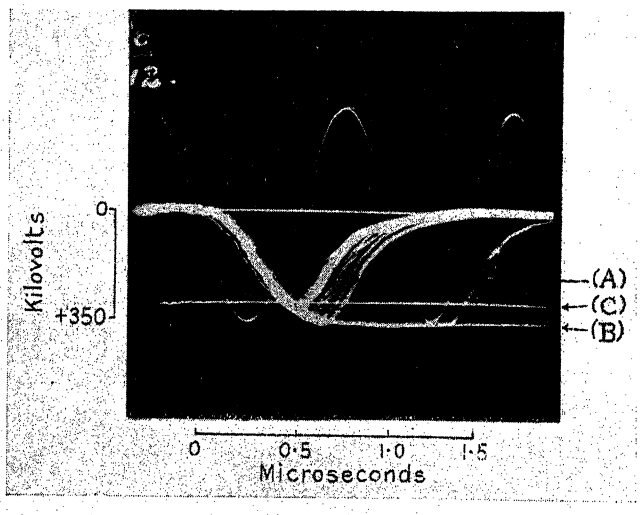


Fig. 8.—13 impulses applied to a sphere-gap set at 82 per cent spark-over.

the most violent induced e.m.f.'s had subsided before the transient had traversed the delay cable (0·4 microsecond).

(8) Performance.

Fig. 7 shows the voltage across a 75-cm diameter sphere-gap, opened too wide for spark-over, when supplied with a 350-kV wave from the impulse generator. It will be seen that the voltage rises above this figure,

* See Bibliography, (24).

reaching a maximum of 400 kV and oscillates. This is to be expected, and has been observed by others.* The wavelength of the oscillations, about 120 metres, is, of course, approximately four times the total length of the conductors forming the high-voltage circuit, plus a slight increase due to the capacitance of the sphere-gap. In Fig. 8 these oscillations have been suppressed

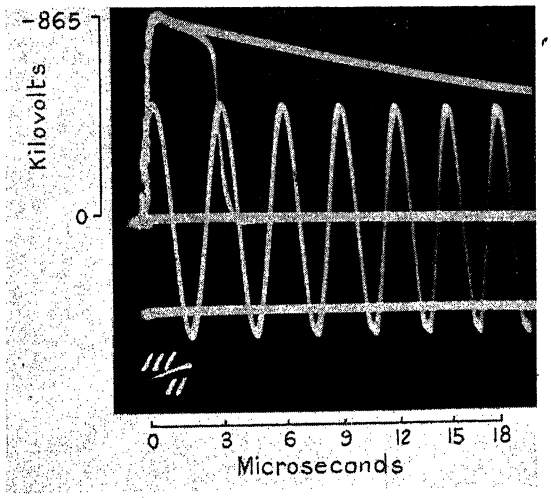


FIG. 9.—Impulse breakdown on a 31-in. point-rod gap.

by including resistance between the impulse generator and the sphere-gap. For this illustration the sphere-gap was first set so that it sparked over for 82 out of 100 applied impulses. Oscillograms of 13 successive impulses were then recorded on the same film. It will be seen that the gap did not always break down at the same

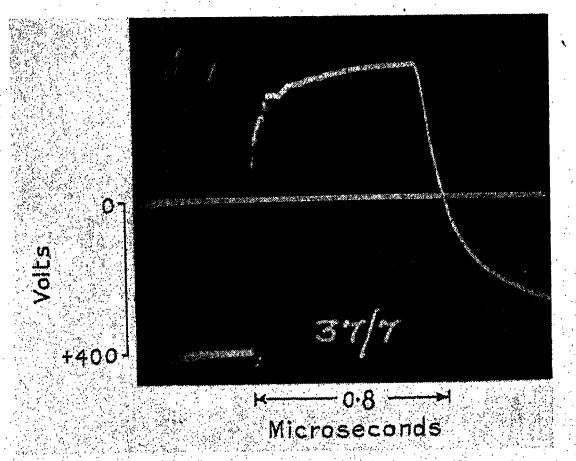


FIG. 10.—Cable discharge wave.

point on the wave, indeed in one case (A) breakdown was delayed until about 0·7 microsecond after full voltage had been attained, while in another case (B) spark-over did not occur at all. The line C is a voltage-calibration line. The coincidence of the wave-fronts in this photograph illustrates the regularity of behaviour both of the trigger-gaps in the impulse generator and of the spark relay in the sweep circuit of the oscillograph. Fig. 9 shows the behaviour of a 31-in. gap between a negatively charged point and an earthed length of channel iron. A 1 000-ohm resistance was included in the high-voltage lead to the point. Two impulses were applied, one of which caused breakdown after a lag of 3 microseconds, while with the other breakdown did not occur.

The application of the oscillograph to low-voltage work is illustrated by Fig. 10, which shows the discharge wave at 400 volts, of 60 metres of 3/·029 in. single-core lead-covered cable, i.e. the voltage at the open end when the other is suddenly short-circuited, the cable being connected to the mercury-cup switch shown in Fig. 4.

In ease and reliability of working the equipment is very satisfactory; over 1 400 oscillograms have been taken. The operator sits in a chair and has all the essential controls within easy reach. He has so little to do that the production of a completely automatic mobile recording instrument, an aim which has been kept in mind throughout, would present no real difficulty.

(9) ACKNOWLEDGMENTS.

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HYDRO-ELECTRIC POWER PRODUCTION IN CANADA.*

By E. C. THORNE.

(*Paper first received 20th February, and in final form 29th June*, 1931.)

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(1) Introduction.
(2) Power production.
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(11) Distribution.
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(13) Tariffs.
(14) Construction.
(15) Tie bank connections.
(16) Industrial development.
(17) Acknowledgment.

(1) INTRODUCTION.

Probably in no other country has the development of hydro-electric power advanced so rapidly as in Canada. The figures issued by the Bureau of Statistics for the year 1930 show that more than 6 million horse-power is now in use in the Dominion, compared with 2½ million horse-power in the year 1919. Further developments are rapidly taking place and big construction schemes, which will materially increase the existing horse-power harnessed, are now in hand. Projects which when investigated some 20 years ago were reported on as unfavourable are now being developed into big hydro-electric power plants and render practicable a constantly increasing area of possible development.

The amount of capital invested in Canada's hydraulic installations has been the subject of intensive study, and the Dominion Water Power Bureau states in its latest bulletin that this investment amounts to almost 1 390 million dollars. Of this amount, 1 168 million dollars, or over 84 per cent, have been expended on lands, buildings, plant, and equipment. This is greater than the capital investment of any other manufacturing industry in the Dominion. The total amount of power installed has grown from 890 000 h.p. at the beginning of the year 1910, to 6 125 012 h.p. In addition, we find that the capacity of central electric stations has grown from 586 502 h.p. to 5 214 336 h.p., and pulp and paper installations from 115 042 h.p. to 579 826 h.p. in the same period.

The capacity of the hydraulic installations of the Dominion now averages 617 h.p. per 1 000 of the population, a figure which places Canada in an outstanding position among the waterpower-using countries of the world.

(2) POWER PRODUCTION.

One of the foremost in the field of hydro-electric power production is the Southern Canada Power Co., Ltd. In the year 1914 the output of this company totalled 4 640 000 kWh, whilst the figures for the year 1930 show an output of 170 865 947 kWh, which is a typical example of the progress made by Canadian hydro-electric power companies.

The company owns and operates five power houses on its system, having an aggregate capacity of 60 000 h.p.; and undeveloped sites throughout the system allow for further development to the extent of 147 000 h.p.

The high-tension transmission lines of the company extend over 463·3 miles, and the distribution lines over 578 miles, the area of supply being approximately 6 000 square miles. The number of municipalities served is 118, and the number of consumers connected is 26 594. The rating of the installed motors amounted for the year 1930 to 45 602 h.p. In addition, the company operates its own telephone system, comprising 423·4 miles of telephone lines.

(3) POWER HOUSES.

The power houses are situated at various points throughout the system. Fig. 1 shows the location of these plants, together with details of the transmission lines and the municipalities served.

On referring to Table 1, giving particulars of the various power houses, it will be seen that the largest of the plants is situated on the St. Francis River at Hemmings Falls.. The capacity of this station is 36 000 h.p., and some details of its construction are given later.

Next in order, we have the Drummondville power house. This is also situated on the St. Francis River, approximately 3 miles down stream from the Hemmings Falls station, and its capacity is 18 000 h.p.

Then comes the Sherbrooke power house of 4 000 h.p. capacity, this station being situated on the Magog River at a point only a few hundred yards upstream from where this river joins the St. Francis.

The next power house is at Burroughs Falls, where a semi-automatic plant of approximately 2 000 h.p. operates under a head of 175 ft. This plant is the company's latest acquisition and was only brought into service during the latter part of 1930.

Finally, we have the Farnham plant of 800 h.p. capacity on the Yamaska River.

With the exception of the Burroughs Falls plant which operates under a head of 175 ft., the heads of water do

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not exceed 55 ft., with the result that the speeds of the machines are low. The hydraulic works vary in design. Hemmings Falls and Drummondville have forebays in the immediate vicinity of the power houses, whilst Sherbrooke and Burroughs Falls are constructed with penstocks. At the Farnham station the water is brought to the machines by canal.

The four alternators at the Drummondville power house are of standard welded-steel design, and are equipped with Kingsbury bearings. Two of these alternators are of Canadian Westinghouse manufacture and are designed for 3 125 kVA at 2 300 volts, 3-phase, 60 frequency. The excitation for these machines is provided by a water-wheel-driven generator rated at 100 kW, at 125 volts. As a standby in case of breakdown, an emergency 150-h.p. motor-generator is also installed. These two alternators are connected to the 2 300-volt busbars, which in turn are connected to No. 1 transformer bank, which consists of three 2 300/48 000-volt 3-phase 3 000-kVA transformers, which feed the high-tension transmission line.

The other two machines are of Canadian General Electric manufacture and are designed for an output of 6 000 kVA at 4 000 volts, 3-phase, 60 frequency. The excitation for these machines is provided by direct-coupled exciters, rated at 100 kW at 125 volts, mounted on the top of the main shaft. These machines are connected to the 4 000-volt busbar which supplies the factories in Drummondville operating at this voltage. Connection is also made to No. 2 transformer bank consisting of three 2 000-kVA 4 000/48 000-volt 3-phase transformers, which feed a second high-tension transmission line.

The two transformer banks are housed inside the power house, and are of the water-cooled type. The control is effected on the high-tension side by remote-control, oil-immersed switches operated from the switchboard. The station itself is supplied from the 2 300-volt busbar through a separate transformer bank, and lightning protective devices are installed inside and outside the power house on the high-tension transmission lines.

The electrical equipment at Hemmings Falls consists of six alternators designed to give 6 000 kVA, 3-phase, at 60 frequency. Two of the machines were originally wound for a frequency of 30 cycles per sec., owing to the fact that they were used solely for supplying power to the Shawinigan Co. which was operating its system

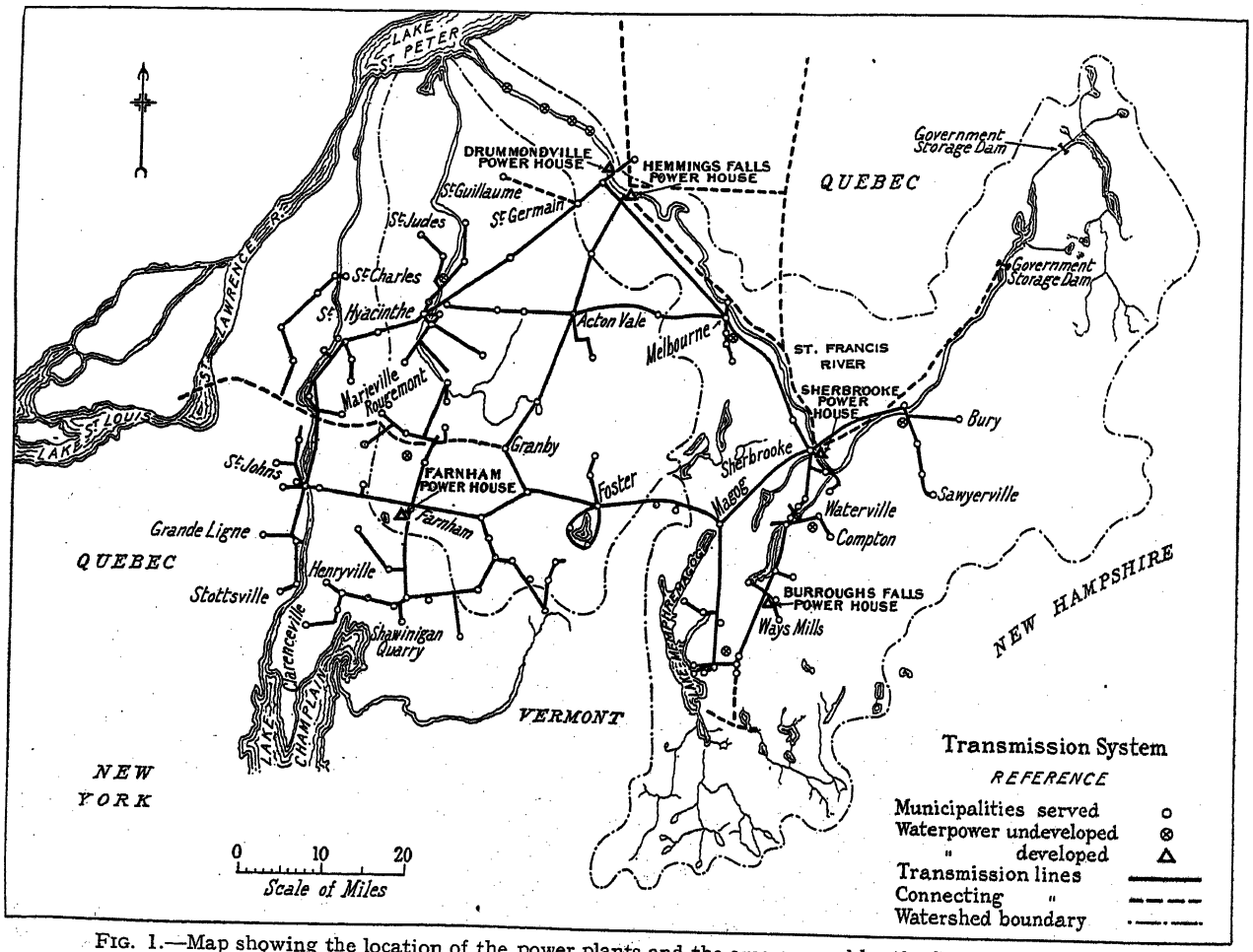


FIG. 1.—Map showing the location of the power plants and the area covered by the Southern Power Co.'s transmission lines.

at that frequency. The Shawinigan Co. has now converted its supply to 60 frequency, and on the completion of the tie bank with this company at Hemmings Falls, the two machines were rewound to correspond to the other four. Further details regarding this tie bank with the Shawinigan Co. will be found later in this paper.

(4) Automatic Power Station.

In September 1930 the Southern Canada Power Co. put into operation its new automatic installation at Burroughs Falls. This plant operates under a head of 175 ft. at a speed of 600 r.p.m., and supplies power at 2 300 volts, 3-phase, 60 frequency. The turbine is of the horizontal variety and was manufactured by Messrs. Morgan Smith & Co., Ltd. The generator, which is a standard welded-steel structure, is of Canadian General Electric manufacture, the governor mechanism being Woodward automatic and oil-operated.

The machine is set in motion by pressing a control button located on the switchboard. This sets the governor mechanism in motion, and, as soon as the machine reaches synchronous speed, the station operator parallels the machine on to the busbars. Thermo-couples are inserted at various points throughout the windings and, in the event of the machine becoming too hot, relays trip the generator switch; at the same time an auxiliary relay in connection with this shuts down the governor mechanism and the entire plant comes to a standstill. In addition to the thermo-couples in the windings, bearing temperatures are looked after in the same way. Over-speed and overload protection are also provided for, relays being incorporated in each of the circuits. As soon as the machine is tripped off the busbars owing to the operation of any of the protective devices, an alarm bell begins to ring.

The power house is a small, brick building on a concrete substructure. The dam is a gravity-type, reinforced concrete structure and is flanked on one bank of the river with an earth-filled dam having a concrete core wall. At its highest point the dam is 68 ft. high, exclusive of the height of the sluice-gate towers.

Out of a total length of 490 ft., 140 ft. is accounted for by the earth-filled dam, 55 ft. by the sluiceway section, and 90 ft. by the spillway, while the concrete wing walls and intake section make up the balance. Over 11 000 cubic yards of concrete were poured into the dam. The flood discharge capacity of the sluicegate and spillway is 8 000 cubic ft. per second, corresponding to 136 cubic ft. per sec. per square mile of drainage area.

The penstock intake has been placed 23 ft. below high water-level to allow a draw-down of 20 ft. from the pond. The head-gate is made of wood and is manually operated by means of a screw hoist and a reduction unit. Two 14 ft. × 20 ft. sluice-gates complete the hydraulic works at the dam. These gates are electrically operated by a single motor, which can be connected to the gear drive of either gate by means of a clutch. The motor is controlled by two push-button stations at convenient points. In addition, the gates are equipped with heaters to facilitate their operation during the winter.

Tests were carried out prior to the machine being put into operation, in order to determine the overall efficiency of the unit, also to make a check upon the friction loss in the intake and pipe line, and to establish curves for recording the permanent stream-flow.

Table 1.

Data Relating to the Power Houses of the Southern Canada Power Co.'s System.

Location, river, and h.p.	Head, ft.	No. of machines	Speed, r.p.m.	Prime movers	Make	Governors	Generators
Hemmings Falls, St. Francis River, 36 000 h.p.	55	6	150	Vertical turbines	Dominion Eng. Co.	Pelton	6 000 V 60 ~ 6 000 kVA
Drummondville, St. Francis River, 18 000 h.p.	30	4	150	Francis type runners	Dominion Eng. Co.	Woodward Pelton	(2) 2 300 V 3 125 kVA (2) 4 000 V 6 000 kVA 60 ~
Sherbrooke, Magog River, 4 000 h.p.	55	3	360	Horizontal turbines	Canadian Boving Co.	Lombard	2 300 V 60 ~ 940 kVA
Burroughs Falls, Nigger River, 2 000 h.p.	175	1	600	Horizontal turbines	Morgan Smith & Co.	Woodward automatic	2 300 V 60 ~ 2 000 kVA
Farnham, Yamaska River, 800 h.p.	26	2	277	Horizontal turbines	Swedish Boving Co.	Oil (Swedish Boving Co.)	2 300 V 60 ~ 300 kVA

The power of the turbine and generator was measured at the generator terminals by using a Weston calibrated wattmeter, which was connected to the switchboard instrument-transformers. The readings of the switchboard wattmeter, as well as of the ammeter and voltmeter, were recorded, the unit being run in parallel with the system throughout the test.

The head-water elevation at the dam was read on a gauge-board installed near the intake. The water-level at the turbine inlet was obtained from a pressure gauge which was connected to a brass pipe tapped into the penstock 6 in. upstream from the face of the butterfly valve, this being about 10 ft. upstream from the centre-line of the turbine. The area of the pipe at this point was 7·9 sq. ft., the pipe being 42 in. in diameter, and the butterfly wicket in the full-open position being 6 in. thick by 42 in. wide.

current. The distance from the upstream face of the trash racks to the electrode was found to be 2 198 ft. Inside measurements of the diameter of the wooden stave-pipe showed it to be within $\frac{1}{16}$ in. of 5 ft. average diameter, giving a total volume between the trash racks and the electrode of 43 000 cubic ft. The quantity of water flowing per second was obtained by dividing 43 000 cubic ft. by the time in seconds for the salt to pass from the intake to the electrode.

Water measurements were made at different gate-openings on the governor. Readings were taken of the head water, tail water, and pressure gauge in the penstock, with the unit shut down in order to establish zero readings; then the unit was started up and run at no load and normal speed, further readings of the pressure gauge and tail water being taken.

The unit was then paralleled with the system, and

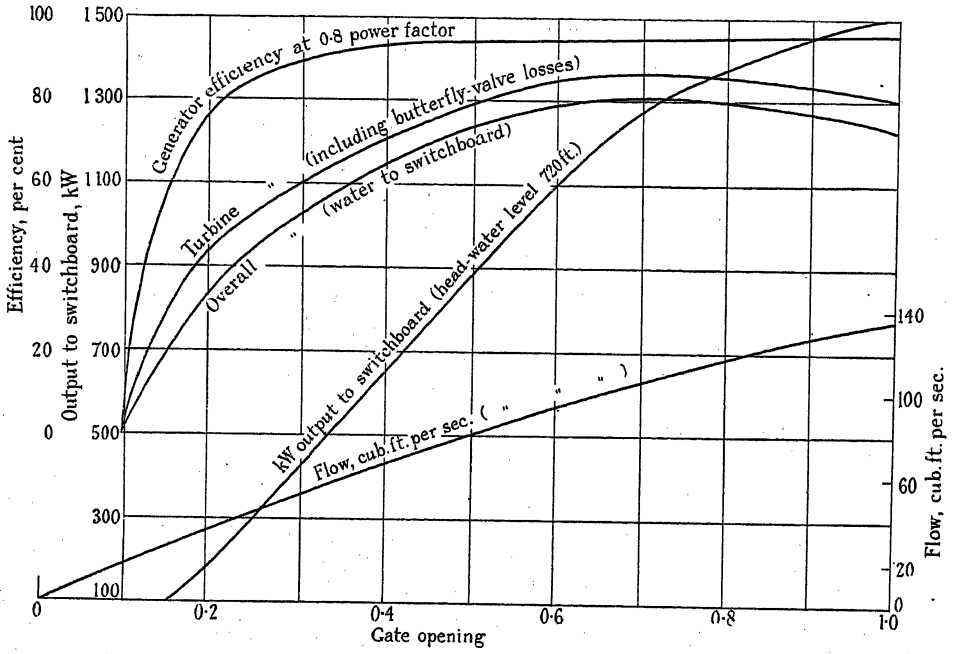


FIG. 2.—Curves showing turbine efficiency at various gate openings.

The quantity of water required for different loads was obtained by recording the time required for a dose of salt to travel down the wooden stave-pipe from the face of the racks to an electrode installed at the lower end of the stave-pipe, just upstream from the surge-tank. A specially-designed bucket containing the salt was lowered into the forebay, just upstream from the trash racks. This bucket was suspended by a rope, and at a given signal a second cord attached to pieces of 10-in. pipe forming the sides of the bucket was pulled, leaving the top and bottom of the bucket stationary and allowing the water to force the salt solution into the upstream end of the pipe.

The electrode consisted of two bars of $\frac{1}{4}$ in. × 2 in. strap iron, supported by insulators and spanning the 5-ft. diameter penstock, an electrical connection being brought out from each bar to a recording wattmeter. The instrument was connected to the 110-volt lighting circuit, with a fixed resistance in series to limit the loaded up to full or 10/10 gate. The bucket was then immersed in the water at a point approximately in the centre of the face of the trash racks, and at a given signal the release cord was pulled. At the same time the starting point was marked on the recording chart of the wattmeter, and readings were taken of head-water level behind the racks, also of the pressure gauge, the wattmeter at the power house, and the tail-water level. At full load it required about $5\frac{1}{2}$ minutes for the salt to pass from the intake to the electrode. Several readings were taken for different gate openings.

The turbine efficiency at the various gate openings is shown in Fig. 2. It includes the loss through the butterfly valve, as it was impossible to get a pressure-gauge connection downstream from the butterfly valve on account of the turbine casing being concreted in. The results show the efficiency, including the butterfly-valve loss, to be 87 per cent. The turbine is guaranteed to give 87 per cent efficiency at approximately 90 per cent

or full load, and also to deliver 2 000 h.p. to the turbine shaft under 165 ft. head. A rough estimate shows that the butterfly-valve losses are in the region of ½ to 1 per cent.

The total friction loss in the length of 2 549 ft. of 5-ft. diameter pipe, comprising 2 177 ft. of wooden pipe and 318 ft. of steel pipe, varies from 5·3 ft. to 0·6 ft. at different flows, this corresponding to a coefficient of friction of between 130 and 140 in Hagen and Williams' tables.

Lake St. Francis station is located 1 000 ft. downstream from the Allard dam at the outlet of Lake St. Francis. The drainage area is 472 square miles. The discharge is measured with a Price current meter, a steel cable being stretched across the river at this point. The gauge readings varied over a period of three years from 193 cubic ft. per sec. at elevation 89·8 ft. to 2 800 cubic ft. per sec. at elevation 94·8 ft. The section of the river at this point is about 150 ft. wide, and the river flow is controlled by the Allard dam.

Sherbrooke station, on the River St. Francis, has a drainage area of 2 626 square miles. Meter readings over three years show a variation in the flow from 763 cubic ft. per sec., for a gauge reading of 0·9, to 20 735 cubic ft. per sec. for a gauge reading of 14·65 ft. The discharge is partly controlled by the Allard and Lake Aylmer dams. The flow curve shows a flow of less than 8 000 cubic ft. per sec. Above that figure the curve is affected by the backwater of the River Magog, which flows into the River St. Francis about ¼ mile below the station.

(5) Hydraulic Works.

The biggest of the power plants on the system at the present time is that at Hemmings Falls on the St. Francis River. The works includes a regulating pond extending some 6 miles up the river. The use of this pond will be very beneficial and will affect future developments below it.

The tributary drainage area is 3 720 square miles and includes a number of lakes of considerable size which are available for storage purposes. Storage facilities have already been provided by the Quebec Government through the agency of the Quebec Streams Commission at Lake St. Francis and Aylmer. There are also privately-owned dams and outlets at Lakes Memphremagog and Little Magog. These, together with others at Brompton Lake and Lake Massawippi, have still to be developed, and it is expected that the St. Francis River will ultimately be controlled to the extent that there will be a reliable flow of 3 000 cubic ft. per sec. The positions of these lakes can be seen from Fig. 1. The flow-duration curve for the year 1925 showed that with the existing storage the flow is maintained at or above 3 000 cubic ft. per sec. during 307 days in the year.

The Hemmings Falls development was started in the year 1923. The power station is situated 2½ miles above Drummondville, at a point where a 15-ft. fall terminates a series of rapids, in which there is a total drop of 50 ft. in a 5-mile stretch of river. The river banks and bed were found to be very favourable at this point and a scheme was adopted consisting of a north wing wall, power-house section, sluice-way section, spillway, and a south wing wall, together with an isolated earth-filled dam. Records for 22 years prior to 1926 show that the flood flow of the St. Francis River was not in excess of 55 000 cubic ft. per sec. It was assumed that a possible run-off of 25 cubic ft. per sec. per square mile is a conservative estimate, and on this basis four 50-ft. sluiceways were provided at an elevation of 299 ft. above sea-level and, in addition, a spillway 507 ft. long, with crest elevation 314 ft. This spillway was provided with facilities for installing temporary flash-boards 5 ft. high, which would permit the head-race water-level to be raised to an elevation of 319 ft. during seasons of low flow. With water at this level, each sluiceway has a discharge capacity of approximately 20 750 cubic ft. per sec., and three or four sluiceways could easily handle the maximum recorded flow. The proposed water-levels were at an elevation of 314 ft. for the head-race and of 264 ft. for the tail-race, giving a gross head of 50 ft.

The spillway section was calculated to resist an ice pressure of 20 000 lb. per linear foot, acting on a line 1 ft. below the crest, plus a hydrostatic pressure corresponding to that condition. This requires a heavier section than is needed to resist water pressure up to an elevation of 321 ft., which would be equivalent to 2 ft. of water running over the top of a 5-ft. flash-board. For the sluiceway section, the crest of which is lower at the elevation 299 ft., the basis of design was water at the elevation 321 ft. with no ice pressure, but allowance was made for ice pressure on the sluiceway piers. These were calculated to resist the pressure transmitted to

Table 2.

Variations in Monthly Flow and Kilowatt Output.

Month (1930)	St Francis R.	Magog R.	Yamaska R.	Total	Daily av. flow	Output*	Daily average
	cub. ft. per sec.	cub. ft. per sec.	cub. ft. per sec.	cub. ft. per sec.	cub. ft. per sec.	kWh	kWh
January ..	232 161	36 136	59 221	327 518	10 565	13 970 760	450 669
February ..	137 832	25 762	26 445	190 039	6 787	12 454 121	444 790
March ..	280 067	60 929	26 266	367 262	11 847	17 383 750	560 766
April	644 863	93 930	37 752	776 545	25 884	15 900 940	530 031
May	366 829	55 113	30 942	452 884	15 096	16 795 175	559 505
June	289 442	70 336	39 424	399 292	13 306	13 988 870	466 295

* The total kWh output shown represents the total generated.

them by the gates, plus the direct pressure on the piers caused by water at the elevation 321 ft. In addition, they were to resist 20 000 lb. ice pressure per foot width of pier acting at the elevation 320 ft.

The sluiceway section between the piers and below the gate was calculated to resist the pressure of water up to the elevation 321 ft., or 22 ft. above the crest. The sections were all developed as gravity sections, but to overcome the uncertainties in construction, and unavoidable joints between batches, vertical reinforcing steel was placed near the upstream face. Since the positions and numbers of the horizontal batch joints could not be foretold, this reinforcement was made continuous.

Owing to the existence of seams of shale at certain points, two rows of $1\frac{3}{4}$ in. diameter anchor rods, running approximately 10 ft. into the underlying rock, were inserted at the heel of the dam to complete an efficient anchorage.

Between the first sluice-gate and the south end of the power house a log and trash chute with stop-logs was provided, 6 ft. in width, and with a bottom elevation of 310 ft., which corresponds to 4 ft. below the crest of the spillway. Below the log chute is a 7-ft. diameter regulating sluice, with its centre at the elevation 301 ft., and provided with an electrically operated pivot valve controlled from the power house. The idea of this is to provide a means of quickly letting through approximately 1 000 cubic ft. of water per sec. in the event of a sudden shut-down of the turbines at a time when, with sluice-gates closed and flash-boards in position, the plants lower down the river would be depending upon the flow of water through the Hemmings Falls plant.

The sluice-gates are of the Stoney roller type, 22 ft. high, with a clear opening 50 ft. wide. Four screw-hoists, with individual motors mounted on an overhead steel structure, operate the four gates. Automatic limit switches guard against over-travel when opening or closing the gates. The gates are provided with electric heaters to allow of their operation during the winter months, and a patent air-bubbler system has been installed for the purpose of keeping the ice sheet from bearing on the gates. This has proved effective, and, in addition, it also prevents the ice from forming in the vertical seal. The velocity of water at the racks is approximately 1·4 ft. per sec., and at the head-gate section 2·7 ft. per sec. The draught tubes are of the Moody spreading type with concrete cones provided with cast-iron caps. The tail race is 500 ft. long and has a minimum section of 1 845 sq. ft. below the elevation 264 ft. It is designed for a velocity of 4 ft. per sec. with water at that elevation and full load on all six units.

(6) Operation.

The entire system is controlled from the offices of the operating department in Drummondville, a building quite apart from the power house. A diagram showing every detail of the system is erected before the operator's desk. On this diagram, tags indicate the number of machines running at the various power houses, and which switches are open or closed throughout the system. Particulars of gangs working on the line are also posted on this board, with details of the work in hand.

Table 3.

	1922	1923	1924	1925	1926	1927	1928	1929	1930
	$	$	$	$	$	$	$	$	$
Electrical revenue ..	714 494	827 295	915 966	1 047 694	1 223 810	1 319 338	1 500 539	1 707 510	1 901 544
Miscellaneous* ..	129 071	126 675	234 897	165 971	165 321	214 942	309 027	388 402	355 877
Gross earnings ..	843 565	953 970	1 150 863	1 213 665	1 389 131	1 534 280	1 809 556	2 095 012	2 257 421
	$	$	$	$	$	$	$	$	$
Purchased power ..	85 406	111 128	129 742	93 908	12 163	19 312	28 274	30 922	69 062
Cost of operation ..	216 075	222 702	240 393	269 472	298 982	319 743	339 722	400 834	432 430
Maintenance.. ..	59 635	59 956	63 570	74 470	82 387	111 296	123 162	186 610	211 415
	361 116	393 786	433 705	437 850	393 532	450 342	491 131	618 366	712 907
No. of consumers ..	13 249	15 066	16 217	18 269	20 065	21 662	23 552	25 543	26 594
Output, kWh ..	41 285 424	46 542 782	48 734 743	84 511 912	122 218 875	123 452 980	138 160 340	164 528 950	170 685 947

* Miscellaneous revenue includes merchandise net profits, and earnings from investments, etc.

The system operator on duty has entire control of the system, and the operators at the power houses have to receive instructions from him before connecting a machine to the busbars, or taking one off. The loads at the power houses are telephoned to the operator hourly, and are plotted by him on a graph sheet. From this graph the system operator is able to observe the load, and as soon as it decreases by a certain amount he gives instructions over the system telephone for a machine to be taken off the busbars at one of the power plants. When the necessary switching has been effected, the power station operator will report to the system operator details of the switching which has been done. The whole operation is recorded on the daily log sheet which the system operator has before him.

Clearances for working parties to effect repairs on the line or other parts of the system which are alive, can be obtained only from the system operator. When a gang arrives at the site of the trouble, the foreman will ring through to the system operator and arrange for the clearance. When the line or apparatus has been made dead, the system operator advises the foreman of the working party. During the time that men are working upon repair jobs the line or apparatus is " tagged " to that effect upon the system operator's board and no switches are closed until the working party have reported all clear.

Operating costs, including maintenance, are given in dollars in Table 3.

(7) Maintenance.

Maintenance of substations is effected by a gang whose job it is to move any faulty transformers, and to repair bushings, substation equipment, and any other apparatus that becomes faulty, including power house equipment. The cost of maintenance can be seen from Table 3. The maintenance gang operates from the Drummondville plant department, and consists of a party of six men, including the driver of the equipment truck with which they are provided. Every necessary tool is carried, including what in Canada is called " hot line equipment," which enables insulators to be changed without interrupting the supply. Spare conductors, insulators, nuts and bolts, insulating material, rubber mats, gloves, etc., are all contained in specially designed compartments built round the body of the truck.

Maintenance of transmission lines is effected by patrol men who are alloted areas for which they are responsible. In the event of a faulty insulator being located, the patrol man immediately reports the matter to the system operator, giving the pole number and the condition of the insulator. He is able to report this from the field, as all he does is to climb up the pole, connect his test set, with which every patrol man is equipped, and ring through to the system operator. If possible the changing of the insulator is left until such a time that the least possible inconvenience is caused by shutting off the supply to that line; this is usually early in the morning or during Sunday, when factories are closed down. In cases of emergency, however, the matter receives immediate attention; the patrol man obtains assistance from the nearest local office, and with the least possible delay the insulator is changed.

Distribution lines are all under the supervision of the local staff for the municipality served, each town having its own office, with a manager and a staff for installation work, meter reading, and the care of the local distribution lines.

(8) Troubles.

Table 4 summarizes the causes of interruptions to the supply during the 12 months ended October 1930. It is obtained by multiplying the number of consumers affected, by the duration of the stoppage in minutes, and dividing by the number of consumers on the whole system. From this we get that the interruptions to the supply represented 0·23 per cent, or that the whole system was out for a period of 12·29 hours. Stated in another way, the operation was 99·77 per cent of perfection.

Table 4.

Interruptions to the Supply during the Year ended October 1930.

	Consumer-minutes / Total number of consumers
Lightning	296·5
Insulators	233·0
Conductors	57·3
Bushings	34·0
Bad operating	34·0
Line repairs, etc.	14·9
Transformers	13·5
Oil switches	13·5
Wind	12·1
Guy wires	6·1
Sleet	5·0
Trees	4·6
Unknown	3·6
Poles	3·4
Miscellaneous	6·0
	737·5 minutes

Most of the troubles experienced throughout the year were due to lightning. Faulty insulators account for the next biggest percentage of troubles; this may be partly due to the fact that the electric strength of some of the insulators may have been reduced owing to a flash-over during a storm. The condition of the insulators is carefully watched, both by patrol men and by linemen, and during the summer months a special insulator tester, which enables the insulators to be tested whilst the line is alive, makes a tour of the system, and weak insulators are marked down on a line report. At the earliest possible moment every insulator that has not passed the test is replaced. Usually the whole line is made dead and every available man on the system assists in the changing of insulators, thereby reducing the length of the stoppage to a minimum.

Each month a meeting of operatives is held at Drummondville. Each power house sends a representative, and all patrol men and members of the operating staff who are available must attend. The business is to discuss troubles, and anyone who has had any during the month states his case. The meeting is presided over

by the operating superintendent, and the entire proceedings are entered in a minute book, a copy of which is forwarded to the head office. Before the meeting breaks up, four demonstrations of resuscitation have to be given by members of the staff. There is thus no excuse for anyone in the employ of the company being unfamiliar with the correct method of performing this operation. Practices are held every week throughout the system.

(9) Substations.

The substations are nearly all of the outdoor type, the more modern ones having steel structures, whilst the earlier constructions are wooden. The transformer banks are usually mounted on concrete bases, although in some cases platforms have been built for mounting the transformers upon. Connections are made delta to delta, there being only one or two exceptions where the bank is delta to star, or star to delta. Substation construction follows standard lines, there being no unusual features. Transformers for outdoor-type substations are nearly all oil-cooled and range from 50 to 3 000 kVA capacity.

There are two exceptions in cooling practice, one at the substation at Sherbrooke, and the other at the switching station at Hemmings Falls. Both these stations have outdoor transformer banks, but in each case they are water-cooled.

The transformer bank at Sherbrooke was the first to be thus equipped, and this was done over six years ago; at that time the Southern Canada Power Co. claimed that it was the pioneer in adopting this practice in Canada. During the winter, temperatures as low as 40 degrees below zero are registered at Sherbrooke; this will give some idea of the conditions under which the transformers operate. This bank consists of three 1 250-kVA transformers, whilst the bank at Hemmings Falls consists of three 5 000-kVA transformers. The Hemmings Falls bank is used in conjunction with the Shawinigan tie, and is a quite recent construction, having been brought into operation only during the latter part of 1930. This bank is at present connected delta to delta, but later is to be changed to star to delta.

(10) Transmission.

The high-tension lines of the company are operated at three voltages: 306·7 miles at 48 000 volts, 42 miles at 22 000 volts, and 114·6 miles at 13 000 volts. The structures are mostly of the wooden variety, although steel towers are used, especially where the spans are long, e.g. at river crossings.

The Shawinigan Company's line, which runs from Three Rivers to Hemmings Falls, is suspended on steel towers the whole way, and where the line crosses the St. Lawrence River special arrangements have been made to vary the tension of the line, the extreme weather conditions making this necessary. In addition, as soon as the river opens up in the spring, heavy shipping traffic passes to and fro beneath this line. This line has been mentioned owing to the fact that through it the Southern Canada Power and the Shawinigan Co. tie their systems together. The height of the wooden structures varies between 35 ft. and 70 ft. H frames are also employed, but in this case only single circuits are carried, whereas a single-pole structure may carry either one or two circuits. Two types of steel tower are employed, the single circuit and the double circuit. The single-circuit tower usually supports the conductors in a horizontal plane at a height varying from 45 ft. to 69 ft. under normal conditions, whilst with the double-circuit tower the conductors are in a vertical plane at a height of from 60 ft. to 100 ft.

(11) Distribution.

Distribution transformers rarely exceed 100 kVA, the majority being between 1 and 25 kVA. For lighting service their spacing varies from 135 to 3 000 ft., the average being between 800 and 1 000 ft. Single-phase transformers are generally used for this service, with 2-wire or 3-wire secondaries.

For power loads the secondaries of the transformers are usually 3-phase delta-connected, and the secondary voltage is in most cases 220 or 550 volts. Distribution is also effected at 4 000 and 2 200 volts for power purposes.

Overload protection is taken care of by fuses, porcelain cut-outs and expulsion-type fuses being mostly employed.

Wooden poles are generally used, and vary in height from 30 ft. to 60 ft. Cross-arms are constructed of wood and are used almost exclusively. The standard dimensions for the arms are:

8-pin arm: $3\frac{1}{2}$ in. × $4\frac{1}{2}$ in. × 9 ft. 2 in., pins 12 in. apart, climbing space 30 in.
6-pin arm: $3\frac{1}{2}$ in. × $4\frac{1}{2}$ in. × 8 ft., pins $14\frac{1}{2}$ in. apart, climbing space 30 in.
4-pin arm: $3\frac{1}{2}$ in. × $4\frac{1}{2}$ in. × 7 ft. 7 in., pins $14\frac{1}{2}$ in. apart, climbing space $14\frac{1}{2}$ in.

Cross-arms situated vertically in the same plane are usually set 24 in. apart; where arms are set at right angles to each other a separation of 12 in. is usual.

Wooden pins and porcelain pin-type insulators are nearly always used, iron pins being employed only in special cases.

The conductors for distribution vary from 500 000 circular mils to No. 6, 4/0, and 2/0 American wire gauge for higher load densities, and No. 2 and No. 4 for the lighter loads. The conductors are generally medium hard-drawn, or soft-drawn copper, with triple-braided weatherproof covering. The configuration is generally horizontal, but where other wires of the same circuit are on another arm, the vertical spacing is almost invariably 24 in. Horizontal pin spacings are usually either 12 in. or $14\frac{1}{2}$ in., the $14\frac{1}{2}$ in. spacing being the most general, as this corresponds to the standard 4-pin and 6-pin cross-arm, the 8-pin cross-arm having a 12-in. pin spacing. For street-lighting circuits No. 6 triple-braided weatherproof wire is the most commonly used, but No. 8 conductors are also employed.

(12) Consumers.

The Southern Canada Power Co. serves altogether 118 municipalities, covering an area of some 6 000 square miles. The total number of consumers connected at the end of the year 1930 amounted to 26 594. Manufacturing concerns account for the biggest load. Drummondville has possibly the largest number of factories,

with Granby next; both these towns have a fair-sized population, and the domestic load is quite big. The growing popularity of electric cooking appliances, refrigerators, and washing-machines is increasing the domestic load, and in several areas new transformer banks have had to be installed to meet the demand. Small towns which at first only required a lighting service have had to have their substations increased in capacity for the same reason. Statistics are contained in Table 5. It will be seen that over a 4-year period there is only a 2½ per cent variation in the connections for the corresponding months.

(13) Tariffs.

General service.—10 cents per unit for first 500 units per month, 8 cents for next 500 units, and 6·66 cents for remainder. Minimum charge $1 per month; discount* 25 per cent; duration 1 year.

Residential service.—$2 per month, plus 4 cents per unit; or 60 cents per month, plus 8 cents per unit. Minimum charge $1 per month; discount 25 per cent; duration 1 year.

Commercial service.—$1 per month, plus 8 cents per unit for first 1 000 units per month, and 6·66 cents for remainder. Minimum charge $1 per month; discount 25 per cent; duration 1 year.

Cooking.—4 cents per unit. Minimum charge $1 per month; duration 1 year; discount 25 per cent.

Heating (Over 1 000 watts).—$1.34 per kW-month. Minimum charge $1.34 per month; discount 25 per cent; duration 1 year.

(*Under 1 000 watts*†).—10 cents per unit; discount 25 per cent.

Tank heaters.—$5.33 per kW-month; discount 25 per cent.

Power contracts.—The following are examples of the tariffs charged for power supplied to factories and consumers who use motors, etc.

Rating	Voltage	Contract	Remarks
Up to 2 h.p.	110	P6, P1‡	Available also for lighting, heating, and cooking.
2 to 10 h.p.	110	P6, P1	
5 to 10 h.p.	550	P6, P1	
10 h.p. (no minimum)	550	P1	
10 to 100 kW..	Primary	P1	
Over 100 kW..	Any primary	P1, P2	

Additional rates are also available for temporary connections, as shown under contract P5.

POWER CONTRACT P1.

Flat rate.

First kW of max. demand	$130 per annum
Second kW	$120 ,,
Third kW	$110 ,,
Fourth kW	$100 ,,
Fifth kW	$90 ,,
Each of next 5 additional kW ..	$80 ,,
Each of next 90 additional kW ..	$70 ,,
Each kW (100 kW minimum) ..	$72.50 ,,

* For payment within 10 days.
† This applies where added to existing lighting, or heating, or cooking.
‡ See below.

Alternative meter rate.

Service charge.	
First kW of max. demand	$8 per month
Second kW	$7 ,,
Third kW	$6 ,,
Fourth kW	$5 ,,
Fifth kW	$4 ,,
Each of next 5 additional kW ..	$3 ,,
Each of next 90 additional kW ..	$2 ,,
Each kW (100 kW minimum) ..	$2.25 ,,

Consumption charges, in addition to service charge:—
For first 50 hours' monthly use of max. demand, 5 cents per unit.
For next 50 hours' monthly use of max. demand, 2½ cents per unit.
For additional consumption, 0·6 cent.

Class A.—Power may be used at any time, charge as above.

Class B.—Power may be used each working day between the hours of 7 a.m. and 6 p.m., 20 per cent discount from above charge.

Table 5.

Number of Lighting and Heating Consumers.

No. of municipalities	Lighting consumers	Heating consumers		Date
		No.	Percentage of total	
89	17 948	2 578	14·4	Dec. 1927
99	19 279	2 982	15·5	Dec. 1928
106	20 781	3 205	15·4	Dec. 1929
114	21 783	3 265	15·0	Dec. 1930

Duration discounts.—Less than 5 years, net; 5 years and over, 20 per cent; 5 per cent allowed for synchronous and condenser equipment; 10 per cent allowed for payment within 10 days.

POWER CONTRACT P2.

Rate for service.

Fixed charge, $1.667 per month per kW of max. demand.
Meter charge, $1.67 per unit for first 50 units per month per kW of max. demand; $1.12 for next 50 units; and $0.883 per unit for remainder.
Discount, 10 per cent if paid within 10 days.

POWER CONTRACT P5.

Power rate.

Service required for one month or less.
$6 per h.p. of rated capacity of motor, payable in advance, plus $2.50 per h.p. per week or fraction thereof, for any service required in excess of 2 weeks, payable weekly in advance.
Service available 24 hours per day except Sundays and legal holidays.

POWER CONTRACT P6.

Fixed charge plus charge per unit.—Fixed charge, based on rated capacity of motor or other apparatus,

of $1.66 per horse-power per month, plus 5 cents per unit. 24-hour service except Sundays and legal holidays.

Consumer pays cost of making service available in this case. When 3-phase service is required an additional $25 is charged towards the cost of metering, plus 35 per cent overhead. All property belongs to the company.

(14) Construction.

All construction work is carried out by a construction gang. New switchgear and apparatus, including new transformers, are installed by this section. For big jobs the assistance of the maintenance gang is sometimes required. This is usually necessary only where heavy transformers have to be moved into position and the use of the equipment truck is required. A line construction gang deals entirely with the construction of new lines throughout the system. Buildings, dam construction, and similar work is handled by the Power Corporation of Canada, who place the work with sub-contractors.

(15) Tie-Bank Connections.

Early in 1931 the Southern Canada Power Co. and the Shawinigan Co. connected their systems through a set of 15 000-kVA transformers at Hemmings Falls. The transformers are at present delta-delta connected with a 50 000-volt connection on the Southern Canada side and a 66 000-volt connection on the Shawinigan system. Later the 66 000-volt connection will be changed to star, giving 110 000 volts. The station is one of the most up to date of its kind using outdoor equipment. The relay protection is all housed in a small brick building centrally located on the substation grounds. The control and metering is all taken care of by a system of conduits brought back to the power house at Hemmings Falls.

Interconnection is of great value both to the Shawinigan Co. and to the Southern Canada Power Co., since low-water conditions occur on the St. Francis River at a different time from those on the St. Maurice River, which is the source of supply of the Shawinigan Co. Interconnection also provides the Southern Canada Power Co. with ample capacity for all peak loads. At periods of high water the excess power on the St. Francis is disposed of to the Shawinigan Co., who find a market for it in electric boilers, or in the large chemical works at Shawinigan.

Additional linking-up is provided with the Montreal Light, Heat, and Power Co. through a Scott-connected bank of transformers of 5 000-kVA capacity, and several smaller connections are available in cases of emergency.

(16) Industrial Development.

Keen interest is taken by the Southern Canada Power Co. in encouraging new plants to start up in its area. For this purpose an industrial department is in operation, which deals entirely with this branch of the business. Over a period of four years this department has brought to the attention of manufacturers throughout the world the unequalled opportunities for economic production that exist in the district. As a result, 43 new industries have been started and give employment to more than 10 000 people.

(17) Acknowledgment.

The author is indebted to the Southern Canada Power Co. for the data contained in this paper.

DISCUSSION ON

"POLYPHASE COMPENSATED COMMUTATOR INDUCTION MOTORS."*

Mr. H. M. Clarke (*communicated*): The fact that the paper obviates the necessity of referring to the circle diagram of the simple induction motor is probably the reason why the author omits the following interesting comparisons. Referring to equation 7 (vol. 70, page 374), it will be noticed that

$$x_c = E_1/2X = E_1/2(x_1 + x_2) \quad \text{and} \quad y_c = kE_1 \cos\beta/2R_2$$

So far as x_c is concerned, the commutator has no effect and the chord of intercept of the x axis in Fig. 22 is the same as for the simple motor. Considering y_c, the case of the simple motor is obtained when k is zero; the centre then lies on the x axis. The size of the circle for the compensated motor only differs from that for the simple motor according to the variations of y_c. The locus of the centre of the circle is a line parallel to the y axis. Unless y_c becomes comparable with x_c, the size of the circle will be only slightly changed. The centre will move in such a way as to give an improvement in power factor, provided $\cos\beta$ is positive. Hence

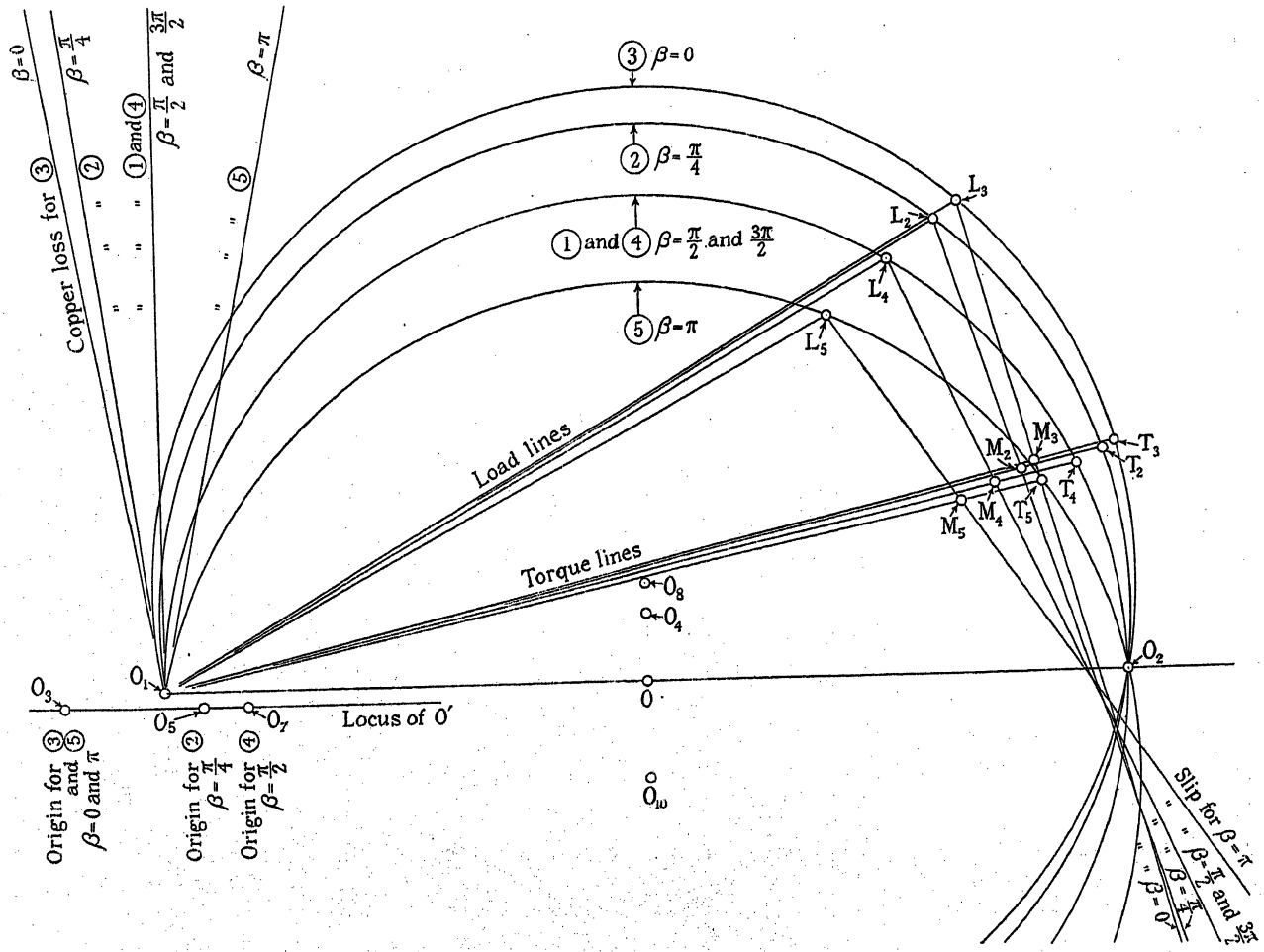


Fig. A.

a nest of circles can be drawn, all passing through O_1 and the other intercept on the x axis, say O_2, their centres all on the right bisector of O_1O_2 and displaced from the x axis according to the value of $kE_1 \cos\beta/2R_2$. As the author points out, the principal effect of the commutator is at O′, the centre of current vectors. The locus of O′ is a line parallel to the x axis and below it by an amount y_n representing the iron loss, just as it would be in the case of the simple motor. The x co-ordinate of O′ is displaced from O_1 by $E_1\left[(k \sin\beta/R_2) - b_0\right]$, or if the usual origin of current vectors for the simple motor be called O_3 (a point on the line $y = y_n$), the new origin O′ is on this line where O_3O' equals $kE_1 \sin\beta/R_2$. To summarize, take the origin of co-ordinates at O_1.

* Paper by Dr. J. J. RUDRA (see vol. 70, p. 365).

then all the circles pass through O_1O_2 with their centres on the line

$$x = E_1/2X \quad \text{at} \quad y_c = kE_1 \cos\beta/2R_2;$$

all the origins O′ lie on the line

$$y = -y_n \quad \text{at} \quad x = E_1[(k \sin\beta/R_2) - b_0].$$

By this means the lines of load, torque, and copper loss pass through the same point O_1 for all values of β. The variation of k may also be studied conveniently. Fig. A illustrates these points.

Another interesting point can be brought out with reference to equation 1 (page 369) and the expression $x_1(I_1 - kI_2)$ for the leakage-reactance drop in the primary. From equation 1 it follows directly that

$$I_1 - kI_2 = I_0 + I_2$$

Now $I_0 + I_2$ is the primary current for the uncompensated motor, and therefore the primary leakage-reactance drop of the simple motor is the same as that of the compensated motor. The author omits a construction for the slip. Referring to Fig. 8, it appears that the term $R_2/[(s + m)(1 + m)]$ is most convenient for this purpose. I think that

(Rotor input)/(Rotor copper-loss)

is equal to $(1 + m)/(s + m)$; this assumption certainly gives the correct result for the simple motor when m is zero. In that case, referring to Fig. 22 (page 377),

$$\begin{aligned}\text{(Rotor input)/(Rotor copper-loss)} &= r_1C_T/R_2C_R) \times (P_T/P_R)\\ &= (r_1C_T/R_2C_R) \times (\sin \mathrm{PO_1T}/\sin \mathrm{PTO_1})\\ &= a(\sin \mathrm{PO_1T}/\sin \mathrm{PTO_1})\end{aligned}$$

where $a = r_1C_T/R_2C_R$

Draw LM parallel to the tangent at T to cut O_1T in M. Join PT to cut LM in S.

Then

$$\sin \mathrm{PO_1T}/\sin \mathrm{PTO_1} = \sin \mathrm{MST}/\sin \mathrm{STM} = \mathrm{MT}/\mathrm{SM},$$

and $(1 + m)/(s + m) = a(\mathrm{MT}/\mathrm{SM})$

When $s = 1$, P moves round to L, and

$$(1 + m)/(1 + m) = a(\mathrm{MT}/\mathrm{LM})$$

Therefore

$$(s + m)/(1 + m) = \mathrm{SM}/\mathrm{LM}$$

When $(s + m)$ is zero, SM is zero, and P coincides with O_1. LM produced in both directions is the slip line, L is at $s = 1$, M is at $(s + m) = 0$, and the length SM is proportional to $(s + m)$.

Dr. J. J. Rudra (*in reply*) : Mr. Clarke's comparison of the various loci of the Osnos motor and his proof of the equality of the leakage-reactance drops in the primary of the Osnos motor and the ordinary induction motor, are interesting and instructive. His construction for the slip is correct, and it forms a valuable addition to my paper. The steps leading to the construction need, however, the following further explanation. The expressions "rotor input" and "rotor copper-loss" in his remarks should read "input to secondary circuit" and "copper loss in secondary circuit" respectively, and it appears from the text that Mr. Clarke really means the expressions I have suggested. A pitfall in the calculations of the Osnos motor is the resistance of the secondary circuit. For reasons already given in the worked-out example on page 378, this resistance should be taken as $R_2/(1 + m)^2$, and not as R_2, as Mr. Clarke has done. After this explanation it is easy to justify Mr. Clarke's assumption that $(1 + m)/(s + m)$ is equal to (Input to secondary)/(Copper loss in secondary). From equation 20 (page 381),

$$\begin{aligned}\frac{1+m}{s+m} &= \frac{yE_1 - r_1I^2}{R_2I^2/(1+m)^2}\\ &= \frac{\text{Input to secondary circuit}}{\text{Copper loss in secondary circuit}}\\ &= \frac{(1+m)^2 2r_1C_TP_T}{2R_2C_RP_R} \quad \text{(see page 377)}\\ &= a\frac{P_T}{P_R}\end{aligned}$$

where $a = (1 + m)^2r_1C_T/(R_2C_R)$

This value for a is $(1 + m)^2$ times that given by Mr. Clarke. The slip can now be obtained correctly either by the construction given by Mr. Clarke or by measuring P_T, and P_R, and making use of the relation $(1+m)/(s+m) = aP_T/P_R$. The latter method is especially convenient if the slip/torque curve is required, as to find the torque one has to measure P_T, and in any case a has to be determined to get the slip.

PROCEEDINGS OF THE INSTITUTION.

826TH ORDINARY MEETING, 21ST JANUARY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 7th January, 1932, were taken as read and were confirmed and signed.

The President announced that the Council had that day elected Mr. W. M. Mordey, Past President, an Honorary Member of the Institution, and also that the eleventh award of the Faraday Medal had been made to Sir Oliver Lodge, D.Sc., F.R.S.

Messrs. F. B. Allcock and J. Whitcher were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see vol. 70, page 473) had been duly elected and transferred.

A paper by Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng., Member, and Mr. W. G. Thompson, Ph.D., B.Sc., Graduate, entitled "The Absolute Measurement of High Electrical Pressures" (see vol. 71, page 1), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

827TH ORDINARY MEETING, 11TH FEBRUARY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 21st January, 1932, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of January, 2 231 donations and subscriptions to the Benevolent Fund had been received, amounting to £1 182. A vote of thanks was accorded to the donors.

A paper by Messrs. W. B. Hird, B.A., and J. B. Mavor, Members, entitled "Electrically-Driven Underground Conveyors in Coal Mines, and their Economic Advantages" (see page 145), was read and discussed.

The meeting terminated at 7.18 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

828TH ORDINARY MEETING, 18TH FEBRUARY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 11th February, 1932, were taken as read and were confirmed and signed.

A paper by Dr. T. Settle, Member, entitled "Commercial Cooking by Electricity" (see page 171), was read and discussed.

The meeting terminated at 7.35 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

829TH ORDINARY MEETING, 25TH FEBRUARY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 18th February, 1932, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. F. L. Best and F. J. Lane were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see vol. 70, page 588), had been duly elected and transferred.

A paper by Mr. H. W. Clothier, Member, entitled "Metal-Clad Switchgear, Automatic Protection, and Remote Control, with particular reference to Developments during the Last Seven Years" (see vol. 71, page 285), was read and discussed.

At 7.32 p.m. the discussion was adjourned to the next meeting.

830TH ORDINARY MEETING, 3RD MARCH, 1932.

Mr. B. Welbourn, Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 25th February, 1932, were taken as read and were confirmed and signed.

The discussion on Mr. Clothier's paper (see page 285), which had been adjourned from the 25th February, was resumed.

The meeting terminated at 8.10 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

INSTITUTION NOTES.

Council for the Year 1932–1933.

The scrutineers appointed at the Ordinary Meeting held on the 21st April, 1932, have reported to the President that the result of the ballot to fill the vacancies which will occur on the Council on the 30th September next is as follows:—

President: Prof. E. W. Marchant, D.Sc.
Vice-President: H. T. Young.
Hon. Treasurer: P. Rosling.
Ordinary Members of Council: (Members) Prof. J. K. Catterson-Smith, A. P. M. Fleming, C.B.E., M.Sc., H. W. H. Richards; (Associate Member) W. S. Burge.

The Council for the year 1932–33 will therefore be constituted as follows:—

President.

Prof. E. W. Marchant, D.Sc.

Past-Presidents.

Colonel R. E. Crompton, C.B.
James Swinburne, F.R.S.
Sir Richard T. Glazebrook, K.C.B., D.Sc., F.R.S.
W. M. Mordey.
Sir John Snell, G.B.E.
Charles P. Sparks, C.B.E.
Roger T. Smith.
Ll. B. Atkinson.
J. S. Highfield.
F. Gill, O.B.E.
A. Russell, M.A., D.Sc., LL.D., F.R.S.
W. B. Woodhouse.
R. A. Chattock.
W. H. Eccles, D.Sc., F.R.S.
Sir Archibald Page.
Lieut.-Colonel K. Edgcumbe, T.D., R.E.T. (Ret.).
Colonel Sir Thomas F. Purves, O.B.E.
Clifford C. Paterson, O.B.E.
J. M. Donaldson, M.C.

Vice-Presidents.

J. M. Kennedy.
R. K. Morcom, C.B.E., M.A.
F. W. Purse.
H. T. Young.

Honorary Treasurer.

P. Rosling.

Ordinary Members of Council.

W. S. Burge.
Prof. J. K. Catterson-Smith.
F. W. Crawter.
A. Ellis.
The Rt. Hon. the Viscount Falmouth.
A. P. M. Fleming, C.B.E., M.Sc.
R. Grierson.
E. W. Hill.
J. F. W. Hooper.
Lieut.-Col. A. G. Lee, O.B.E., M.C.
C. Le Maistre, C.B.E.
H. A. Ratcliff.
E. H. Rayner, M.A., Sc.D.
H. W. H. Richards.
R. H. Schofield.
R. P. Sloan, C.B.E.
J. W. J. Townley.
V. Watlington, M.B.E.

And the Chairman and immediate Past-Chairman of each Local Centre.

Students' Premiums.

In addition to the Premiums mentioned on pages 143 and 144, the Council have awarded the following Premiums for Students' papers for the session 1931–32:—

Premiums of the value of £10 each:

Author	*Title of Paper*	*Where read*
P. McKenna	"The Engineer in Business"	Liverpool and Manchester
H. H. Taylour, B.Sc.(Eng.)	"Mercury-Arc Rectifier Phenomena"	London
C. T. Webster and H. T. Price	"Three-Phase A.C. Commutator Motors"	Newcastle

Premiums of the value of £5 each:

W. R. Bishop	"A Short-Wave Broadcast Transmitter"	London
J. R. Kennedy, B.Sc.	"Some Problems in the Design and Economics of the E.H.T. Overhead Line"	Newcastle
C. F. Lawrence	"The Construction and Operation of a 200-line Private Automatic Exchange"	Liverpool
H. Lillie	"Noise"	Edinburgh
W. D. Oliphant, B.Sc.	"Theory and Design of the Gramophone Pick-up"	London
F. Roberts	"Photo-Electric Cells"	Manchester
A. G. Shreeve	"A.C. Contactors: their Design and Service"	Chester
R. L. Spiller, B.Sc.(Eng.)	"Pyrometry"	Sheffield
C. S. Whiteley	"Power Supply to Direct-Current Traction Systems"	Liverpool and Manchester

The Students' Prize.

The above prize has been awarded for the session 1931–32 to Mr. T. A. Long for his paper on "The Relations between Economics and Engineering."

The Page Prize.

The above Prize has been awarded for the session 1931–32 to Mr. C. F. Booth for his thesis entitled "The Post Office Radio-Frequency Measuring Installation at Colney Interception Station, Frequency Range 15–24 000 Kilocycles per Second."

The award for the session 1930–31 was made to Mr. J. R. Shewan for his thesis entitled "The Theoretical and Practical Training of the Apprentice Electrician."

Graduateship Examination Results: May, 1932.

*Passed.**

Adamson, W. (Barnsley).
Bailey, O. F. (Northampton).
Bancroft, H. D. (Bradford).
Bates, J. L. (Nuneaton).
Beck, C. (Scarborough).
Belcher, C. A. (London).
Bell, J. C. G. (Belfast).
Bevan, K. J. (London).
Bradshaw, R. V. (Bristol).
Bridgewater, T. H. (Sutton).
Bugden, A. G. (Sutton).
Burgess, A. H. (Romiley).
Burman, H. P. (Northwood).
Burston, R. F. (Wolverhampton).
Chaloner, B. S. (Pontypool).
Chen, S. H. (Southampton).
Chrisp, J. H. O. (Newcastle-on-Tyne).
Clewett, W. H. (Torquay).
Cooke, A. (Rotherham).
Cuthbert, R. (Cowdenbeath).
Dallow, J. C. (Isleworth).
Dance, G. (Nottingham).
Davis, R. C. (Breadsall).
Denholm, N. H. (Newcastle-on-Tyne).
Edwards, H. J. (Dartford).
Findlay, A. B. (Dundee).
Francis, E. G. (Plymouth).
Frost, M. G. (London).
Galle, G. A. (Stafford).
Grove, D. S. (Ilford).
Holmes, C. T. (Hull).
Horsfield, J. (Stockport).
House, L. E. (Devonport).
Isaac, F. C. (Plymouth).
Jamieson, D. (London).
Jamieson, G. J. (London).
Kennan, L. W. (Dublin).
McKearney, P. (Birkenhead).
Mackie, A. D. (Lochgelly).
Mackridge, T. (Burnley).
Marples, E. I. B. (Lausanne).
Matthews, T. F. (Tredegar).
Ninnim, L. C. (Southampton).
Norman, S. J. (Newark).
Northcott, W. J. O. (Plymouth).
Parsons, D. R. (Lichfield).
Penstone, W. St. G. (London).
Perry, J. R. (Norwich).
Raymond, G. E. R. (Devonport).
Shaw, C. W. (Hull).
Simpson, C. (Dunfermline).
Smart, G. W. (Harrogate).
Sumner, W. (Hillingdon).
Tagholm, L. F. (Swansea).
Taylor, F. E. (Radcliffe-on-Trent).
Thorley, T. (Denton).
Throsby, F. S. (Leicester).
Tyler, B. (Northampton).
Walmsley, F. C. (Woodford Green).
Warwick, G. A. (Surbiton).
West, W. C. (Hull).
Wheat, R. H. (Harrogate).
Wolfenden, R. F. (Liverpool).
Wood, R. L. (Mansfield).
Wright, J. A. (Heanor).
Wykes, J. P. (London).

Passed Part I only.

Aubin, R. E. L. (London).
Bedingham, A. S. (Nuneaton).
Chatterji, S. N. (London).
Dean, H. (Mansfield).
Dickson, W. S. (Welwyn).
Dunn, W. K. (Manchester).
Foster, R. S. (Croydon).
Goodman, G. P. (London).
Hartham, E. P. (Manchester).
Heiser, E. J. (East Barnet).
Hetherington, T. (Watford).
Hill, P. (Yeovil).
Ledger, H. H. (Nottingham).
Lemmon, F. C. (Brentwood).
Lockett, T. H. (London).
Maxwell, S. W. (Mansfield).
Scholefield, S. (Stone).
Warner, N. E. (Lincoln).

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed Part II only.

Barton, H. H. (Nottingham).
Bedford, H. (Barnsley).
Burton, L. (Barnsley).
Cross, W. R. (Nottingham).
Dixon, B. (Doncaster).
Foggo, J. M. (Walsall).
Francis, R. B. (Wallington).
Golding, R. C. (Kibworth).
Graham, W. D. (Stafford).
Greenwood, H. (Burnley).
Griffin, R. (Nottingham).
Griffiths, J. H. (Ebbw Vale).
Henzell, M. P. (Newcastle-on-Tyne).
Horley, F. A. (London).
Hughes, C. E. (Rhondda).
Lowde, E. A. (London).
MacLennan, H. B. (Greenock).
Meakins, C. (Walsall).
Pawley, G. F. (Cardiff).
Powell, C. A. (Enfield).
Stewart, A. (King's Lynn).
Tattershall, J. (Barnsley).
Westlake, A. E. (Newcastle-on-Tyne).

Elections and Transfers of Members.

At the Ordinary Meeting held on the 21st April, 1932, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

De Salis, Rodolph Henry F., Commander, R.N.
Drake, Francis Vernon.
Grant, Allan, B.Sc.
Kendall, Roy, Captain, Aust. Signals.
Orchard, John Richard S., M.A.
Patton, William Archibald H., B.Sc.
Perowne, Lancelot Edgar C. M., Captain, R.E.
Rogers, Sumner Barnes.
Triggs, William Warren, M.Sc., B.E.
Webber, Arthur Frederick, B.Sc.(Eng.).
Wood, John Alexander.

Companions.

Cox, Charles Horace.
Legge, Reginald Francis, Brig.-General, C.B.E., D.S.O.

Associate.

Bray, Percy Archibald.

Graduates.

Brown, Vincent Walker, B.Sc.Tech.
Davidson, George Hunter.
Durrani, Mohamed Ubaidullah K.
Herbert, John Ferguson, B.E.
Innes, George Smith, B.Sc.
Jeffs, Harold.
Johnson, Frederick William, B.Sc.
Lawson, Ernest Watson.
Matthews, Roland.
Mody, Rustom Jehangir, B.Eng.
Platt, Alfred Dennis B.
Sadden, Edward William.
Sahai, Haridev.
Scotson, Geoffrey Richard F., B.A.
Shanahan, Daniel, B.E., B.Sc.
Small, Charles John P., B.Sc.(Eng.).
Thompson, Thomas Eric, B.Sc.
Thorn, Jack Gane.
Todd, John Renwick, B.Sc.
Trenhail, William Patrick.
Wajnerowicz, Jacob, B.Eng.

Students.

Adlard, Wyndham Roy.
Ashton, Norman.
Bates, Arthur William.
Bennett, David Paterson.
Bennison, Sydney.
Boag, John Wilson.

Students—continued.

Boardman, Albert Edward.
Brown, Frederick Herbert S.
Callow, Alfred Dan.
Chorley, John Michael.
Cleverley, Alfred James.
Collins, John Edward.
Cousland, Sidney Thomas G.
Croft, Norman Benjamin.
Cunuder, Felix John.
Davies, Frederic Randall E.
Davies, Theodore John C.
Dawson, William Henry.
Dorling, Eric Alexander J.
Evans, Francis William.
Evans, John.
Fairley, Eric Samuel.
Green, Harold Edgar.
Guidera, Philip Creagh.
Hardman, Wilfrid Adams.
Hayward, Cyril.
Huff, Sam Henry.
Hyde, Norman Eric.
Insley, Leonard Robert.
Ives, Francis Lochart.
Jeffs, Eric Arthur.
Jenkins, Llewellyn Evans.
Johnson, Geoffrey.
Larkum, Wilfred.
Malcolm, Robert Denis
Mean, Clarence H.
Midgley, Frank.
Moore, Paul James R.
Moorhouse, Thomas Albert C.
Morgan, Piers Anthony.
Nepean, Evan Yorke, B.A.
New, Charles Morley.
Nye, Philip.
Parry, Donald John C.
Pepworth, Frederick James.
Phillips, Richard Keith.
Pike, Alan Robert.
Potter, Robert Douglas.
Prince, Harry Leslie.
Pritchard, William Henry.
Proude, Leslie.
Short, Ernest Leslie.
Sims, Kenneth Edward.
Smith, Donald Edwin.
Thomas, Alan Rosser.
Thomson, Frederick George
Vipond, Wilfred Henry.
Wall, Clifford Anthony.
Waters, Bernard Smith.
White, Raymond Denbigh.
Whiteman, Spencer William.
Williams, John Cambray.
Zweigbergk, Charles.

TRANSFERS.

Associate Member to Member.

Browne, Arthur William.
Dickinson, James, M.A., M.Eng.
Harris, Thomas Emlyn.
Lydall, William Myers.
McKichan, John James, O.B.E.
Trewman, Professor Harry Frederick, M.A.

Associate to Associate Member.

Allan, John Edward.

Graduate to Associate Member.

Austin, Basil Brougham, B.Eng.
Dawes, Arthur Robert.
Fielder, Cecil Redvers.
Forsyth, John Hugh, B.Sc.
Griffin, Raymond Walter, B.Sc.(Eng.).
Humphriss, Eric Allan, B.Sc.(Eng.).
Latta, Matthew Garnet.
Partridge, Norman George R., B.Sc.(Eng.).
Powell, Hugh Morgan, B.Sc. (Eng.).
Reith, Ewart Laurence.
Telemat, Shafik Mustafa.
Thornton, Edward Charles B.
Vigoureux, Joseph Paul E., M.Sc.

Student to Associate Member.

Macwhirter, Robert, B.Sc.
Skillman, Thomas Samuel, M.A.

Student to Associate.

Whittle, George Edwin.

In addition the following transfers have been effected by the Council:—

Student to Graduate.

Berman, Moses Elia, B.Eng.
Bristow, Geoffrey William, B.Sc.(Eng.).
Dinwoodie, Thomas Blount.
Hall, Leslie Edward, B.Sc. (Eng.).
Mew, Gordon Merrifield, B.Sc.(Eng.).
Parr, William Henry T.
Shivapuri, Pandit Ratan N.
Singh, Kehar.
Toy, William Bentley H.
Tringham, William Stuart L.
Wade, Geoffrey Parkes, B.Sc.
Walker, Eric Hallam, B.Sc.
Wilcock, Albert.
Wilkinson, John Bevis.
Wilson-Dickson, William Gordon.
Wood, Sidney Thomas, B.Sc.Tech.

STUDIES IN RADIO TRANSMISSION.

By T. L. ECKERSLEY, B.A., B.Sc.

(*Paper first received* 17*th December*, 1931, *and in final form* 9*th February*, 1932; *read before the* WIRELESS SECTION 23*rd March*, 1932.)

SUMMARY.

With the advent of short-wave telegraphy, a new technique of echo and facsimile measurement has been developed, facilitating signal-intensity measurements in the wavelength range between 14 and 50 metres. Part (1) of this paper deals with the method adopted of making facsimile measurements, and describes the results obtained, whilst in Part (2) the author discusses transmission problems in the light of these data and suggests the theoretical methods to be employed in solving such problems.

Part (3) discusses the problem of scattering, while in Part (4) the author deals with theory.

LIST OF SYMBOLS.

t = time.
λ = wavelength.
$\overline{\lambda}$ = wavelength in ionized layer = $\lambda c/u$.
k = $2\pi/\lambda$.
ν = frequency.
ν_0 = critical frequency in ionized medium $Ne^2c^2/(\pi m)$.
N_s = electronic density, electrons per cm^3.
e = charge on electron, $1{\cdot}59 \times 10^{-20}$ electromagnetic units.
m = mass of electron, $0{\cdot}9 \times 10^{-27}$ gramme.
c = velocity of light = 3×10^{10} cm/sec.
δ, d, x, y, z = distances, lengths, or co-ordinates.
V_p = phase velocity.
U = group velocity.
v = velocity.
τ = interval of time (facsimile echo times).
$\tau_c = 1/\nu_c$ = mean time between electronic collisions.
θ = angle of ray elevation (or scattering angle).
ϕ = angle subtended by transmission path at centre of earth.
R = range, i.e. $R_0\phi$.
R_0 = radius of earth.
h = effective height of Heaviside layer.
h_0 = actual height of apex of ray.
n = ray order.
l, m, n = direction cosines.
μ = refractive index.
r = radius vector from centre of earth (or other co-ordinate centre).
γ = recombination coefficient.
I = rate of production of ions.
H = height of homogeneous atmosphere.
β = absorption coefficient of ultra-violet light (or angle).
S = intensity of sun's radiation.
ρ = density (atmospheric).
E = electric force (generally microvolts per metre).

LIST OF SYMBOLS—*continued.*

W = power radiated (watts).
d_0 = skip distance.
α = attenuation coefficient.
α_z or α_c = attenuation factor given by $\nu_c/(\pi\nu)$.
T = optical thickness of layer.
Z_0 = depth of penetration of ray into the Kennelly-Heaviside layer at normal incidence.
σ = conductivity (or parameter for determining recombination curves).
$2\pi S$ = resultant phase in electromagnetic wave.
$\delta\chi$ = change of phase (and amplitude) at reflection from the Kennelly-Heaviside layer.

INTRODUCTION.

It is a truism that science advances with the ability to make measurements. In the past the progress of our understanding of radio transmission phenomena has been much impeded by the technical difficulties involved in making such measurements. During the past decade, however, the difficulties have been largely overcome and, with the advent of short-wave telegraphy, not only has a new technique of echo and facsimile measurement been developed, but the progress of absolute signal-intensity measurement has been so far perfected that we have recently been able to make a large number of signal-intensity measurements in the wavelength range between 14 and 50 m. By the help of the facsimile apparatus we have also been able to make a large number of echo measurements. The results so obtained, discussed in this paper, are of great help in analysing the processes of transmission.

Such signal measurements as we were able to make were not complete. Only the horizontal component of the magnetic field in the wave-front was measured. A complete specification would require the simultaneous measurement of the fields in three perpendicular directions, as well as the relative phases of the components.

Such a series of measurements would obviously be difficult, if not impossible, in the present state of the art, and we have to be content with something on a much smaller scale. The observations here given comprise measurements of the normal component of the field in the received wave of some of the more important commercial stations working in the range between 14 and 45 m. They were made systematically throughout the course of a whole year.

Now measurements alone are not sufficient. Progress can only be made in so far as the difficulties of interpretation can be overcome. These difficulties lie partly in the variability of the measured signal, which makes repeatable observations difficult to obtain and introduces

considerable uncertainty into the final results, and a corresponding uncertainty in the comparison with theory, and partly in the inability to arrange suitable experiments. We have to take measurements to suit the exigencies of the traffic services.

The interpretation of these results is greatly helped by the set of observations of facsimile echoes which is included in this paper. The facsimile apparatus acts as a sort of oscillograph, and records the rapid variation of signal intensity and multiple echoes which follow the reception of very short impulses. Thus, when such short impulses are transmitted, the arrival of the signal by various paths is made evident by the separate marks on the receiver record. These results are of the greatest value in interpreting the geometry of the rays. It may be observed, however, that they give little information as regards the energy content of the rays, which the first set of measurements supplies. The discussion of ray geometry and field intensities thus falls naturally into two almost completely separate parts.

The facsimile observations are particularly valuable, as a simple geometrical ray theory can be applied where the waves are short enough, and definite and simple interpretations of the results can be made. Such interpretations are subject to reservations which, however, are now well known, so that no lack of rigour in the ray treatment can be imputed where such reservations are taken account of.

This short-wave material, although still incomplete, can be used to lay bare the secrets of the Heaviside layer. Short waves are specially suitable for this purpose because they penetrate the regions far beyond those accessible by long waves, and because the results of measurements are, as stated above, so much easier to interpret than long-wave transmission results, where a ray theory is inadmissible and a more complex wave theory has to be used.

The knowledge of the electrical constitution of the upper regions of the atmosphere so obtained can be used in developing a theory of radio transmission; and although the data are insufficient for an accurate specification of the numerical values of the transmission constants they are sufficient to indicate the general form of the dependence of these on wavelength, season, latitude, local time, etc. Even where the data are insufficient for this purpose they are still sufficient to indicate the theoretical methods to be employed in the solution of transmission problems, and in particular to show that optical ray methods are only applicable to the short-wave range ($\lambda < 200$–300 m), and that the complete wave methods must be used for the longer waves. The author therefore proposes, in the first part of the paper, to discuss the facsimile and intensity results, aided by information of the same kind obtained by other investigators, and to deduce a representative, though incomplete, model of the Heaviside layer in so far as it affects radio transmission. In the second part of this paper he proposes to deal with transmission problems in the light of these data, and to discuss the nature of the theoretical methods to be used in solving them, and in analysing radio data in the whole range of wavelengths. This, in broad outline, represents the trend of development of our research in the last two years, and a discussion on these lines seems a fitting continuation to the author's series of papers on radio transmission published in the *Journal* during the last 10 years.

PART (1). FACSIMILE MEASUREMENTS.

The object of these experiments is to record, at the receiving end, a pulse emitted at the transmitting end. For this purpose the facsimile apparatus, the principle of which can be gathered from the skeleton diagram shown in Fig. 1, is used.

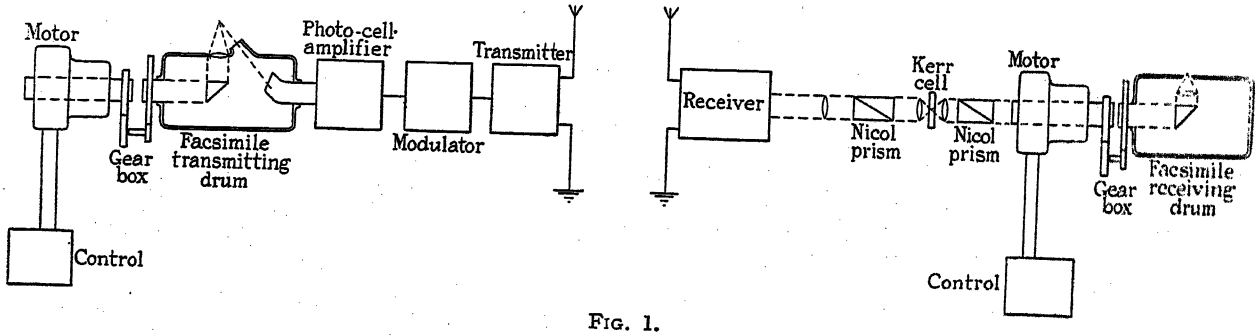


FIG. 1.

Although this is not the place to enter into a full discussion of facsimile methods, sufficient explanation should be given to make the records perfectly clear. The message to be sent is placed on a drum, and a spot of light from a rotating optical system is caused to scan the message. The reflected light from the picture is led to a photo cell. As the spot of light sweeps over the picture the intensity of the light in the photo cell varies in proportion to the light and shade in the picture. The output of the photo cell is made, by known methods, to modulate the transmitter. A similar optical system revolving in synchronism at the receiving end is used to record the signals and reproduce them as a picture. Thus a light-sensitive paper is mounted on a drum similar to the transmitting drum, and a scanning spot of light (revolving, as before stated, in synchronism with the transmitter) traverses this recording paper. The received signal is made to modulate the light intensity (by means of a Kerr cell or Moore lamp) so that the record on the print is really a record of the variation of the received signal intensity and in this respect is similar to an oscillographic record, except that amplitudes, represented by the density of the images produced, are difficult to estimate except qualitatively. The time scale

is very accurately known since it is controlled by the scanning speed of the light spot, which in its turn depends on the speed of rotation of the optical system controlled by the master oscillator.

In the original experiments made in 1923 (New York to the Marconi beam receiving station, Somerton, Somerset) scanning speeds of 30 in. per sec. (76·2 cm per sec.) were generally used, although speeds as high as 120 in. per sec. were occasionally tried. In the former case ($v = 76{\cdot}2$ cm per sec.) 1 millisecond corresponds to a distance of 0·762 mm, an interval easily measured if the images are sharp enough.

To reproduce distinctly short echoes, which are separated by the order of 1 millisecond, the duration of the pulse sent should be small compared with this, so that the direct signal and the echo should not overlap. The sharpest pulse that can be sent depends on a number of circumstances. When there are long transmission lines between the facsimile apparatus and the transmitter or receiver, it is generally these which limit the sharpness of the signals sent. The speed of scanning, thickness of the line to be reproduced, and minimum diameter of the spot of light, are the limiting factors when there are only

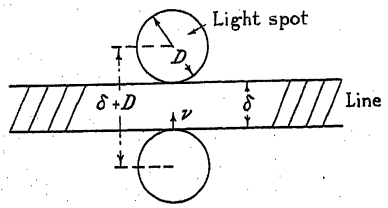


FIG. 2.

short lines between the facsimile transmitter and radio transmitter.

Thus, if δ is the thickness of the line and v the scanning speed of the spot of light, the duration of the pulse will be δ/v when the spot of light is infinitely small. It is, however, not practicable to reduce the light-spot diameter below a certain limit (0·01 in. is the usual diameter, so that when this is a finite diameter, D say, the total duration of the pulse is the interval between the moment when the leading edge of the spot of light touches the line and the moment when the lagging edge leaves the line, i.e. $(\delta + D)/v$ (see Fig. 2).

It is obvious that there is no great gain in reducing the thickness of the line δ to a small fraction of D, for D is then the controlling factor. Hence in the later experiments the thickness of the line δ was always made 0·01 in., and the total duration of the pulse was $0{\cdot}02(1/v)$ sec.

The dot builds up and dies away gradually. Full intensity only occurs for $0{\cdot}01(1/v)$ sec. With a scanning speed of 30 in. per sec. the duration of the dot is then between 0·00033 sec. and 0·00066 sec., in general quite sufficient to separate images 1 millisecond apart. Recently, however, in view of the prevalence of echoes, the maximum scanning speed was reduced to 14·4 in. per sec., and although, for the purpose of facsimile records, this speed is found to be sufficient, for the recording of echoes it is too slow.

In such a case 1 millisecond is represented by 0·366 mm, and the shortest pulse lies between 0·0014 sec. and 0·0007 sec., which is rather too small to separate millisecond echoes clearly. The distance 0·366 mm per millisecond is too small to measure accurately in view of the blurring of the start and finish of the marks recorded on the receiver print.

To obviate this last difficulty, one of the older facsimile receivers was set up at Somerton and run at a multiple of the speed of the transmitter. It was found that the best pictures were obtained with a reception speed four times the transmission speed. A little consideration will show that with a picture that is composed of 0·01 in. lines ruled across the direction of scan, a similar type of picture is received.

The time scale is increased fourfold, and although the marks of each individual pulse—caused by the scanning of the line—are rather longer than desirable, the records appear to be adequate for determining the "spread" of the signal, i.e. the duration between the first and last echo. This, from the practical point of view of finding the maximum speed of transmission without distortion, is all the information that is required. From the theoretical point of view also, it gives the main, if not the complete, information required.

FACSIMILE RESULTS.

The facsimile results can be made to yield a great deal of information. Before entering into the detailed method of analysis it may be as well to recapitulate, in a summary manner, the general ideas on which the analysis depends, and the assumptions which must be made.

These have already been partly discussed in a previous paper.*

In discussing transmission phenomena some difficulty is encountered in using a consistent nomenclature. The subject is still very much in a state of flux. There are, as yet, no accepted names for the various layers, some even conjectural, which together constitute the upper ionized regions of the atmosphere.

In a recent discussion on the ionization of the upper atmosphere the opinion of the majority was in favour of confining the name "Kennelly-Heaviside layer" to the lower ionized region at the height of approximately 100 km above the earth. This, however, leaves the upper ionized regions from 200 to 350 km unnamed. In view of present usage in many quarters, it seems to the author to be preferable to use the name "Kennelly-Heaviside layer" to include the whole of the ionized region, and to distinguish the parts by the labels E and F, E referring to the lower regions at about 100 km and F to the upper region above 170 km, sufficient evidence having been obtained recently to show that these two parts are normally separate. It should be clear, then, in what sense the names Kennelly-Heaviside layer, E layer, and F layer are used throughout the paper.

Returning, after this digression, to the discussion of facsimile reproduction, we find that the received facsimile records disclose in general a series of 1, 2, 3, 4 or more separated marks corresponding to the arrival, by different paths, of a single transmitted impulse.

The differences of the times of arrival can be measured

* T. L. ECKERSLEY: "Multiple Signals in Short-Wave Transmission," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 113.

with considerable accuracy. It is from these measured time differences that the ray angles, effective layer height, and maximum electronic density in the Kennelly-Heaviside layer can be found. To illustrate how this may be done, we can take the simple case of a flat earth and assume that the gradient in the layer is purely vertical. Neither of these assumptions is justified, and in the more refined method to be described later the curvature of the earth is taken into account, at least to an extent which very considerably reduces the errors involved, in all but exceptional cases. The assumption of a vertical gradient has to remain, but the consistency of the final results, involving this assumption, gives assurance that we are not greatly in error on this account.

The analysis is based ultimately on the well-known theorem that the time taken by a pulse projected along a ray at an angle of elevation θ to traverse the actual paths TP′QS′ . . . . R (see Fig. 3) is equal to the time taken by light to traverse the equivalent path TPQS . . . . R, and is

$$\frac{d}{c\cos\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where TR = d.

The difference in time of any two echoes, or " echo spread " as we may call it, is

$$\tau_{12} = \frac{d}{c}\left(\frac{1}{\cos\theta_2} - \frac{1}{\cos\theta_1}\right) \quad . \quad . \quad . \quad . \quad (2)$$

where θ_1 and θ_2 are the corresponding angles of projection of the two rays. τ_{12} is measured. It is the time separation between any two echoes on the record. d being known, it is possible to find $1/(\cos\theta_2) - 1/(\cos\theta_1)$. The final step is made in assuming that the first mark is made by a signal for which θ_1 is very small, i.e. by a glancing angle for which $\theta_1 = 0$, so that finally we obtain $(1/\cos\theta_2) - 1$ and can determine the angle of the rays recorded. We may put this in another way. τ_{12} is the difference in time of traversing the path of signal $_2$ and signal $_1$, say $\tau_2 - \tau_1$.

Now $\tau_2 = \dfrac{d}{c\cos\theta_2}$ so that

$$\tau_{12}\,(\text{measured}) = \tau_2 - \tau_1 = \frac{d}{c\cos\theta_2} - \tau_1 \quad . \quad (3)$$

If τ_1 is known, θ_2 can be computed. The assumption involved in this analysis is that τ_1 is known with sufficient accuracy to determine θ_2 also within certain limits of accuracy. The uncertainty in the values of N, h, etc., depends essentially on the uncertainty of estimating τ_1.

The uncertainty is greatest when θ_2 is small, for the percentage error for a given error in τ_1 is greatest when θ_1 and θ_2 are small. The greatest weight should be given to observations where θ is large.

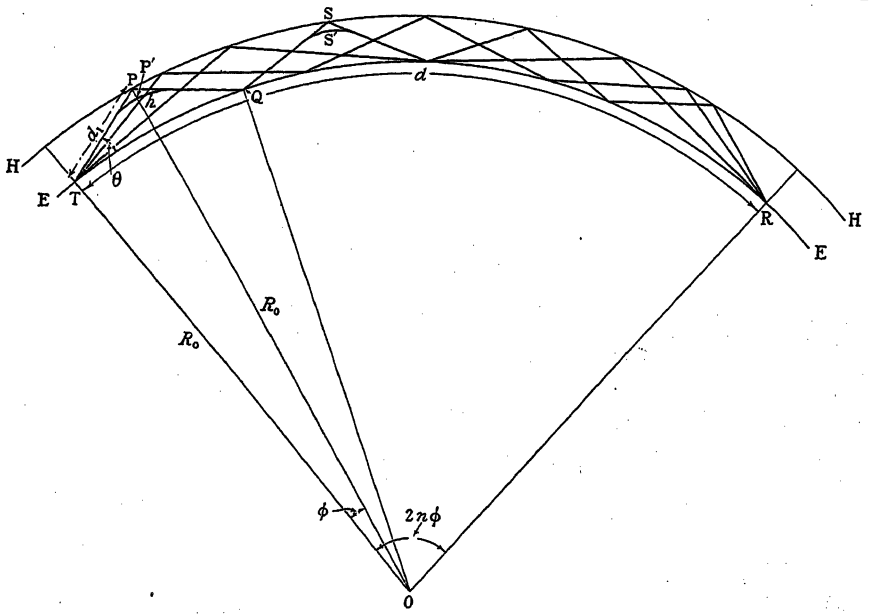


FIG. 3.

As regards the mode of transmission, the simplest assumption to make is that the energy of sufficiently short waves* travels from T to R (see Fig. 3) in a series of multiple reflections between the earth and the F layer. This assumption, which will be adhered to throughout, is, the author feels, entirely justified by results. For high-angle transmissions, e.g. those recorded for 60 m and 120 m between Writtle, near Chelmsford, and Somerton, the echoes are so regular that they can be definitely fitted into a scheme of multiple reflection (within the errors of experiment). For shallow-angle transmission the echo times are more irregular, and some difficulty in fitting is sometimes found.

The author attributes this irregularity to small-angle scattering in the upper layer. It is smoothed out in taking the means. In dealing with this analysis we have to introduce the idea of the " order of the ray."

* Shallow-angle rays with $\lambda > 18$ m may be reflected at the E layer.

Thus we may define an nth order ray as one which, in traversing the distance between receiver and transmitter, is reflected n times from the Kennelly-Heaviside layer. A first-order ray is one that covers the whole distance in one jump, a second-order ray is one that requires two jumps, etc. Although in the determination of the ray angle θ the assumed order of the ray is not of any consequence, it does become of importance in determining the effective height, for we have in the example shown in Fig. 3 the choice of assuming that the effective height is h, say, for a first-order ray, and $\frac{1}{2}h$ for a second-order ray.

When the orders are small the alternatives are so far separated that it is easy to make a choice, but where the order is large, as in the case of long-distance transmission, it is not always easy to decide between an nth order and an $(n+1)$th order ray, say between a 9th order and a 10th order ray, since the alternative effective heights differ by only about 10 per cent.

The uncertainty in the ray order makes itself felt in estimating τ_1, the delay time of the first ray. Added to this is the uncertainty whether the glancing-angle first ray is kept down below the lower E layer or not. The values of τ_1 can, however, be estimated in many cases from the results of measurements of round-the-world echo time. This presumably corresponds to the time τ_1 of the facsimile echoes, increased in the ratio of the world circumference to the facsimile transmission distance, where the latter is well beyond the skip distance and an appreciable fraction of the earth's circumference.

Now a knowledge of the angle θ enables one to determine the electronic density in the Heaviside layer necessary to reflect the ray of this angle.

The relation on which this is based is*

$$\cos\theta = \frac{R_0 + h_0}{R_0}\sqrt{\left[1 - \frac{Ne^2c^2}{\pi m\nu^2}\right]} \quad . \quad . \quad (4)$$

or approximately, when h_0/R_0 is a small quantity, as it always is,

$$\frac{Ne^2c^2}{\pi m\nu^2} = \sin^2\theta + 2x \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where $x = h_0/R_0$.

What this naturally implies is that the greater the ray angle, the greater the electronic density required for reflection, and for a given angle the greater the wave frequency and the greater the density required. The formula also shows that there is a certain critical angle corresponding to a given maximum density in the layer, such that rays of greater angle are not reflected, but escape. This critical angle is given by

$$\sin^2\theta = \frac{N_{max.}e^2c^2}{\pi m\nu^2} - 2x \quad . \quad . \quad . \quad . \quad (6)$$

Observation shows that in general there is a finite number of echoes, usually of comparable intensity. The maximum delay time between the first and last echo measures the maximum ray angle recorded. This echo delay in general decreases with increasing frequency, and has a diurnal variation, suggesting that it is correlated with the maximum layer density.

It is assumed, in general, that longer delay echoes are not present because they correspond to rays which escape through the layer—that, in fact, the last echo is caused by a ray which has the greatest angle possible, i.e. just less than the critical angle. On this assumption the echo delay time is a measure of the maximum electronic density in the upper atmosphere, and this is the more accurate the higher the order number of the ray.

It is conceivable, of course, that there may be enough electronic density to reflect higher-angle rays than those represented on the record, and that the failure to show any echoes of such delay is due to the excessive attenuation of these high-angle rays. Examples of such conditions certainly have been observed. For instance, the echo times recorded for the South Africa 16-m transmission at about midday are often much less than those recorded slightly earlier or slightly later in the day (see Fig. 5). It is hardly possible that the F layer density has suddenly largely decreased during this period—indeed, this is the time when it should be a maximum—so that the only explanation is that the higher-angle rays are eliminated at such a time by attenuation. Nevertheless, the echo time delay gives a very faithful measure of the maximum density in the layer in all but exceptional cases, which usually bear signs indicating their exceptional nature.

It will be observed that the calculated maximum density depends on the actual height of the ray apex through the term x in equation (3). Now x is the ratio of the *actual* height of the apex of the ray to the radius of the earth. This quantity is not determined by the analysis, although the effective height h is. Using h instead of h_0, we get a close approximation which is a slight over-estimate of N. Now we have seen that h has a range of uncertainty dependent on the most suitable choice of the order n of the ray, this uncertainty becoming less as n becomes greater. But large values of n usually imply high angles, so that again more weight must be given to the higher-angle rays, especially in view of the fact that the correction to N on account of x becomes less the greater the value of $\sin^2\theta$ compared with $2x$.

In the more refined analysis, taking account of the earth's curvature, the influence of the choice of h is found to be considerably smaller than shown above, so that uncertainties on this account are not serious, and the main uncertainty lies in the choice of τ_1.

Very briefly, then, the maximum echo delay time measures the maximum ray angle, and hence the maximum layer densities, and, when the ray order is known, the effective height of the layer. These calculations are subject to uncertainties, firstly in respect to the estimate of τ_1, the time taken by the initial pulse or signal, which affects all subsequent calculations of N and h, and secondly with respect to the choice of the order n, which directly affects the calculated effective height and, through x, to a minor extent the values of $N_{max.}$ It is explained that more weight should be given to the results derived from high-angle rays than to those derived from low-angle rays, since the percentage importance of the uncertainties is less in the former case.

* See, for instance, "Multiple Signals in Short-Wave Transmission," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 113; also equations (13) to (16) on page 411.

Method of Calculating the Results of Facsimile Echo Work.

We shall now consider in detail the geometry of what we may call the generalized equivalent rays, which bear a close relation to the equivalent rays as normally defined.

Outline of Theory

(*a*) *Geometrical Principles.*—In Fig. 3 let the distance between the transmitter T and the receiver R be d, and let the echo under consideration make n reflections at the layer. Call the angular distance from T to R, i.e. $\angle$ TOR, $2n\phi$, and the radius of the earth R_0. Then we have:—

$$d = 2nR_0\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

If c is the velocity of light, then light will traverse a distance d in a time d/c.

We now define a time τ such that the actual time taken for the nth order echo we are considering to reach R from T is $(d/c) + \tau$. Actually the velocity of the signal will vary during the journey, since in the layer it travels with the group velocity which depends on the density of the layer. If the energy did travel with the constant velocity c, it would traverse a distance which we will call $2nd_1$, where

$$2nd_1 = d + c\tau \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The time τ is the amount by which the actual time of travel of a pulse exceeds the time taken by light to traverse the arc TR. τ is very nearly, but not quite, the echo time between the main initial signal and the nth echo disclosed by the facsimile record. d_1 may be called the generalized equivalent ray path.

It is obvious that we can represent the distance d_1 geometrically in the way shown in the diagram at TP, drawn for $n = 4$, and that this representation gives us a simple picture of the approximate way in which a ray passes from T to R. For the moment we shall consider the problem to be a purely geometrical one, and shall discuss later the connection between it and the physical problem with which we are really concerned, noting that the connecting link is the definition of the time τ. The distance d_1 is a subsidiary quantity defined by equation (8) and chosen to give a geometrical picture approximating to the unknown geometry of the actual ray path.

If θ is the angle of elevation at T, then $\angle$ PTO $= \frac{1}{2}\pi + \theta$, and, since $\angle$ TOP $= \phi$ by definition of ϕ from equation (7), it follows that $\angle$ TPO $= \frac{1}{2}\pi - \theta - \phi$. Letting PO $= R_0 + h$, we have from Δ TOP

$$\frac{d_1}{\sin\phi} = \frac{R_0}{\sin(\frac{1}{2}\pi - \theta - \phi)} = \frac{R_0 + h}{\sin(\frac{1}{2}\pi + \theta)}$$

or

$$\frac{d_1}{\sin\phi} = \frac{R_0}{\cos(\theta + \phi)} = \frac{R_0 + h}{\cos\theta} \quad . \quad . \quad . \quad (9)$$

Knowing τ and assuming a value for n, d_1 and ϕ are known from equations (7) and (8), and so, from equation (9),

$$\cos(\theta + \phi) = \frac{R_0 \sin\phi}{d} = \frac{2nR_0 \sin\phi}{d + c\tau} \quad . \quad (10)$$

whence $(\theta + \phi)$ is known, and thus θ is known. Then again, from equation (9),

$$R_0 + h = \frac{R_0 \cos\theta}{\cos(\theta + \phi)} \quad . \quad . \quad . \quad (11)$$

and so h is known.

Thus, given τ and n, both θ and h are known, and for any given value of d a series of curves can be drawn, with the height h as ordinates and the time τ as abscissæ, for a set of integral values of n (see Fig. 4). If distances are measured in kilometres and time in milliseconds, $R = 6\,366$ km and $c = 300$ km per millisecond.

When d gets large, there may be a lower limit to n which is greater than unity, since θ must be greater than zero. Equation (11) leads at once to the limit for $\theta = 0$.

$$(R_0 + h)\cos\phi = R_0$$

i.e.

$$h = R_0(\sec\phi - 1) = R_0\left(\sec\frac{d}{2nR_0} - 1\right) \quad . \quad (12)$$

This equation gives the lower limit to n below which,

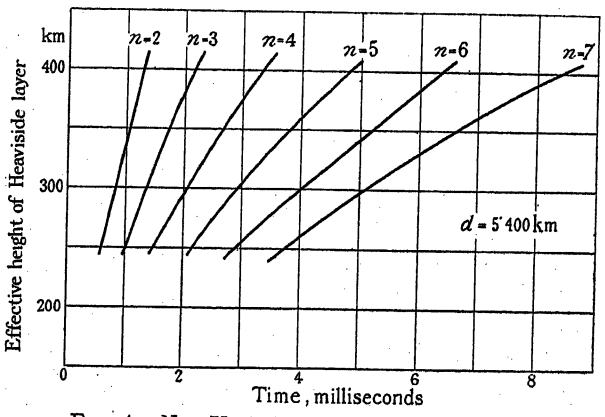


Fig. 4.—New York–Somerton ($d = 5\,400$ km).

to make the geometry possible, h would have to be greater than is consistent with the actual experimental facts.

(*b*) *Physical Principles.*—In the light of the work of Eccles, Larmor, Appleton, Breit and Tuve, and others, particularly Appleton* and Schaefer and Goodall,† we can anticipate the results and accept the general physical picture of two distinct layers, a lower one at about a height of 100 km, and an upper one between 200 and 350 km. The lower layer has an ionic density of about 10^5 ions per cm^3 and is responsible for the reflection of long wireless waves. The upper layer has a considerably higher density and is capable of reflecting short waves which escape through the lower layer. The so-called "reflection" is really a process of refraction due to a density gradient in the layer, and the relation between the refractive index and density can be worked out by the electromagnetic theory, and has been applied by Eccles to the Kennelly-Heaviside layer.

If N is the ionic density at any point in the layer

* E. V. Appleton and A. L. Green: *Proceedings of the Royal Society*, A, 1930, vol. 128, p. 163.

† J. P. Schaefer and W. M. Goodall: *Proceedings of the Institute of Radio Engineers*, 1931, vol. 19, p. 1437.

and ν the frequency of the wave traversing the layer, the refractive index μ at the point is given by

$$\mu^2 = 1 - \frac{Ne^2c^2}{\pi m\nu^2} \quad . \quad . \quad . \quad . \quad (13)$$

where e is the charge on the ion (i.e. electron) in electromagnetic units, and m is the mass of the electron in grammes.

This may be written

$$\mu^2 = 1 - \frac{\nu_0^2}{\nu^2}$$

where $$\nu_0^2 = Ne^2c^2/(\pi m) \quad . \quad . \quad . \quad . \quad (14)$$

ν_0 being the critical frequency in the layer at the point considered.

As the density N increases, the refractive index becomes smaller and the upward ray is gradually bent round and, provided N gets large enough, is turned down to earth again. The exact path by which the ray traverses the layer depends on the gradient of the layer, but if the angle of elevation at the surface of the earth (where $\mu = 1$) is θ_0, then it follows that the maximum height, as determined by ray theory, to which the ray penetrates, is given by h_0, where

$$(R_0 + h_0)\mu = R_0 \cos\theta_0$$

μ being the refractive index at the height h_0. Substituting from equation (13),

$$1 - \frac{Ne^2c^2}{\pi m\nu^2} = \left(\frac{R_0}{R_0 + h_0}\right)^2 \cos^2\theta_0 \quad . \quad . \quad (15)$$

Writing $x = h_0/R_0$ and using the relation (14) we have:—

$$1 - \frac{\nu_0^2}{\nu^2} = \frac{1}{(1+x)^2}\cos^2\theta_0$$

$$= (1 - 2x + 3x^2 - \ . \ . \ .)\cos^2\theta_0$$

$$\therefore \ \frac{\nu_0^2}{\nu^2} \simeq \sin^2\theta_0 + 2x\cos^2\theta_0$$

or, if θ_0 is small but not in comparison with x,

$$\frac{\nu_0^2}{\nu^2} = \sin^2\theta_0 + 2x \quad . \quad . \quad . \quad . \quad (16)$$

This expression shows the maximum value that θ_0 can have for a wave of frequency ν to be reflected from a layer in which the maximum density corresponds to a critical frequency ν_0. Rays starting with larger values of θ_0 escape through the layer. We thus have an upper limit to the order of the reflection which is directly related to the maximum density in the layer.

For short waves the lower layer produces very slight bending, and the ray travels in an almost straight line until it reaches the upper layer. Provided the initial angle is not too large the ray will be bent round and returned to earth again, unless the maximum density is insufficient to bend down even the rays which leave the earth at a glancing angle, e.g. late at night for very short waves. As the gradient of the layer may vary at a given height, from place to place along the course of the journey the angle at which the reflected ray strikes the earth may differ from the initial angle of elevation, and if it makes several reflections between the transmitter and the receiver the spans of the several reflections may not be equal and the maximum height may vary from one reflection to another. This would apply especially for an east to west transmission. Owing to lack of information, however, we assume that the layers of equal density are concentric with the earth's surface over the distance considered, since this assumption is found to lead to reasonable results.

The ray path is thus assumed to be similar to the geometrical form given above, except that it is rounded off at the top. If the earth be assumed to be flat and the layer parallel to it, it can be shown that the time taken by the actual curved path would be the same as if the ray travelled with the velocity c in a straight line to an apex and down again; but with a curved surface and layer this result becomes slightly modified.

Whereas the angle of elevation called θ in the geometrical argument should be equal to the angle θ_0 for the flat earth by virtue of the above stated theorem, there will be a slight difference in the actual case of the curved earth. If t is the time taken by the ray to reach its maximum height, h_0, and if ϕ is the corresponding angle subtended at the centre of the earth, then it can be shown that t is given by

$$t = \int_0^{\phi} \frac{r^2 d\phi}{cR_0\cos\theta_0} \quad . \quad . \quad . \quad . \quad (17)$$

where r is the radius vector from the centre of the earth. Since r increases from R_0 to $(R_0 + h_0)$ as ϕ increases from 0 to ϕ, it follows that t lies between $R_0\phi/(c\cos\theta_0)$ and $(R_0 + 2h_0)\phi/(c\cos\theta_0)$ approximately, and may be represented by

$$t = \frac{(R_0 + \delta h_0)\phi}{c\cos\theta_0}$$

where δ has a value of about unity.

Using the same time t we deduce an equivalent height and an angle θ corresponding to a distance d, as in the geometrical theory, and get

$$t = d_1/c \quad \text{and} \quad \frac{d_1}{\sin\phi} = \frac{R_0 + h}{\cos\theta}$$

$$\therefore \ t = \frac{R_0 + h}{c\cos\theta}\sin\phi \quad . \quad . \quad . \quad . \quad (18)$$

The relation between θ and θ_0 for the curved earth is therefore given by

$$\frac{(R_0 + \delta h_0)\phi}{c\cos\theta_0} = \frac{(R + h)}{c\cos\theta}\sin\phi$$

In applying equation (15) to determine N we have

$$\frac{Ne^2c^2}{\pi m\nu^2} = 1 - \frac{R_0^2}{(R_0 + h_0)^2}\cos^2\theta_0 \quad . \quad . \quad (19)$$

and since the time between the transmitter and receiver is $2nt$, assuming n reflections where t is as above, and therefore $2nt = (d/c) + \tau$ by definition of τ, then

$$\cos\theta_0 = \frac{(R_0+\delta h_0)}{c2nt}\phi \,.\, 2n$$

$$= \frac{(R_0+\delta h_0)}{R_0}\frac{d}{d+c\tau} \text{ (since } d = 2nR_0\phi)$$

$$\therefore Ne^2c^2/(\pi m\nu^2) = 1-(R_0+\delta h_0)^2/(R_0+h_0)^2 \times d^2/(d+c\tau)^2$$

If we assume $\delta = 1$, this gives

$$N = \frac{\pi m\nu^2}{e^2c^2}\left[\frac{c\tau(2d+c\tau)}{(d+c\tau)^2}\right]$$

$$= \frac{\pi m}{e^2\lambda^2}\left[\frac{c\tau(2d+c\tau)}{(d+c\tau)^2}\right]$$

where λ is the wavelength.

If λ is measured in metres, inserting the values for m and e, the expression becomes

$$N = \frac{1{\cdot}117\times 10^9}{\lambda^2}\left[\frac{c\tau(2d+c\tau)}{(d+c\tau)^2}\right] \quad . \quad . \quad (20)$$

For small values of τ the expression in the brackets approximates to $2c\tau/d$, but for practical purposes it is best to draw a series of graphs for required values of d and λ.

If δ is not equal to unity, this would involve a correction term of about $2(1-\delta)h_0/(R_0+h_0)$ inside the brackets in (20), but it is in general negligible, and the limits of error of experiment do not warrant its inclusion, even if δ were known.

Application to Facsimile Measurements.

The measurement of the facsimile records gives us in effect a value for the time τ, and also, from a knowledge of the G.M.T. at the receiver and the highest-order echo present, an approximate method of determining the rate of recombination in the F layer during the night. As recombination proceeds the higher echoes disappear in turn, giving the time at which each corresponds to the maximum density in the layer at the moment of its disappearance.

The determination of the time τ presents a difficulty, since it is not directly given by measurement. The main signal on the records does not correspond to the direct path over the surface of the earth, but usually to the lowest-order reflection possible, as determined by equation (12). It therefore itself corresponds to some time τ_0, and if the time interval between the main signal and some particular echo is τ' (obtained directly by measurement) the time τ required for our equation is given by

$$\tau = \tau' + \tau_0 \quad . \quad . \quad . \quad . \quad (21)$$

We must therefore make an estimate of τ_0, and this proves to involve an uncertainty which may in some cases be serious. The main signal corresponds to a very small angle of elevation, and during the daytime and for part of the night may be held down or seriously modified by the E layer. The time τ_0 may therefore be much smaller than it would be if the lower layer had no effect. This suggests taking as a lower limit the value zero, and as an upper limit, the time that a ray would take if there were no E layer present. We may possibly by these means obtain some information as to the behaviour of glancing rays. It is obvious that the difference between the two points of view will be most marked on the short echoes. The problem would be much more definite if conditions in the layer remained constant, and accurate and consistent measurements of the time τ' could be made, but in general a reasonably accurate value of τ' can only be obtained by averaging a large number of readings which vary considerably among themselves.

The following method is very useful in deciding the probable order of the echoes. When the average τ' values have been obtained for the various echoes, the values are marked off along a time scale and fitted to the set of $(h\tau)$ curves drawn for the given distance d with the same time scale. The origin for the scale of τ' values must be adjusted to lie on the curve corresponding to the order of the main signal, or on the axis if τ_0 is to be assumed zero. If there is any marked difference in the height h for the different-order echoes this should be apparent with $\tau_0 = 0$, and if τ_0 is not assumed equal to zero some allowance should be made in the fitting of the time scale to the curves to take account of variations in h. In general, however, the results are not sufficiently accurate to admit of these refinements in adjustment. It is a matter of using discretion in individual cases, and actual practice in fitting the values to the curves will give a better idea of the process than can be conveyed in words. When the appropriate value of τ_0 has been decided the $(h\tau)$ curves give the values of h and n. It is usually obvious which value of n to choose, and the corresponding ionic density is determined directly from equation (20), remembering that $\tau = \tau' + \tau_0$ from equation (21). For this purpose it is convenient to draw a graph, with N as ordinates and τ as abscissæ, for each set of stations and wavelength.

It has been shown that it is uncertain just to which part of the course between the transmitter and receiver the density N deduced corresponds. In developing the theory it has been assumed, in order to simplify the geometry, that the density is uniform along the path at any given height. Experiment shows that from this point of view the assumption was justified, or, in other words, variations which do exist do not seriously affect the geometry. In determining the recombination curve, it is necessary to know something of the variations of density along the course, especially if it is desired to obtain by extrapolation from the recombination curve the value of N at sunset. In an east and west transmission the times of sunset at transmitter and receiver may differ by several hours, and an idea must be formed as to the position of that part of the layer which really determines the longest echo that can be transmitted.

In general the least dense part of the course will be situated over one station or the other, dependent on the time of day. Thus in an east to west transmission the density is least during the night over the eastern station, since the night is more advanced and the recombination further advanced than over the western station. But at sunrise at the eastern station the place of least density moves along the course westward until it is over the western station. Account must be taken of this trans-

ference in using an all-day facsimile run to deduce a curve showing the variation of ionic density with local time.

Discussion of Results.

The material consists of a large number of facsimile records taken during April, May, June, and July, 1931, on stations at Kliphevrel, South Africa (wavelengths 16·1 and 33·7 m) and Drummondville, Montreal, Canada (16·5 and 32 m). Each record comprises a reproduction of a sheet ruled with lines 0·01 in. thick and 1 in. apart.

The records were transmitted with the maximum available scanning speed of 14·4 in. per sec., and in practically every case were received at a scanning speed exactly four times this. Each picture comprises the recording of over 1 000 individual pulses and their associated echoes. Examples of parts of enlarged records are shown on Plates 1 and 2 (between pages 420 and 421).

There are altogether 35 sheets on Montreal (32 m), 24 on Montreal (16 m), 49 on South Africa (33·7 m), and 208 on South Africa (16 m), together with various others (13) taken on the 37-m beam station at Dorchester to show scattering. A number of the 22-m New York–Somerton records were also selected for re-examination. These were run at the same scanning speed at receiver and transmitter. The scanning speed in this case was 30 in. per sec.

Together with these are the records of two facsimile tests between Writtle, near Chelmsford, and Somerton, Somerset, (distance 227 km) on 60 m and 120 m, carried out in 1929, which will be discussed in due course.

The method of dealing with this rather formidable amount of material was as follows:—The sheets were examined one by one, and those which gave measurable echoes were selected for measurement. Each sheet usually afforded 20 or 30 measurements chosen more or less at random. Special attention was paid to a series of records taken at intervals of about 1½ hours throughout the night on 30-m transmissions from Montreal and South Africa. These show, as has already been explained, a regular decrease of echo time as the night advances (illustrated in the examples of Plate 1), and a corresponding decrease in density. The variation of density with time after sunset, when the ionizing agent is removed, gives a very good measure of the recombination in the upper atmosphere.

The salient features of the material, which can be taken in at a glance and without elaborate measurements, are illustrated by the few examples shown. Consider Montreal first. Two records typical of conditions between 1900 and 2000 G.M.T. taken on 32 m and 16·4 m respectively are shown [Plate 2 (1) and (2)]. The former gives a maximum echo spread of about 5 milliseconds, with traces at about 6 milliseconds, while the latter gives a spread of 0·95 millisecond. Thus the 16-m transmission is very much freer from long echo than the 32-m transmission, the echo spread on 16 m being less than one-fifth of that on 32 m. This is in complete accord with the results predicted in the author's paper "Multiple Signals in Short-Wave Transmission,"* where a large reduction in echo time with wavelengths is predicted.

* *Loc. cit.*

Theoretically, in equivalent F-layer conditions the echo spread should be proportional to the transmission distance, and so we might expect the South African echo spreads to be nearly double those on the Montreal route. Actually for 33-m transmission this is by no means the case, and the reason for this can be seen on examining the South Africa–Somerton path. During the early summer season, when the results were taken, the northern part of the route is well in daylight when the southern part is close to sunset, when the maximum echo delays might be expected, but it is not until nearly three or four hours later, after sunset at Somerton, that any successful facsimile transmission on this wavelength can be obtained. At this time the maximum density at the South African end is so much reduced that high-angle rays are no longer to be expected.

But even where at about 1900 G.M.T. facsimile transmission can be obtained, the echo times are less than would be expected from the conditions at the South African end. This result can be attributed to the absorption of the high-angle rays in traversing the rather long route from South Africa, a conclusion which derives some weight from the following observations. A series of records was taken on South Africa throughout the night of the 21st–22nd May, 1931. Although the first of these was taken some hours after sunset at South Africa, the echo time actually increased initially and then dropped in the normal manner towards sunrise at South Africa. This can hardly imply that layer density actually increased from 1900 to 2100 G.M.T., but must imply that the higher-angle rays, which should have been present from 1900 to 2100 G.M.T., were attenuated in travelling the long distance.

These results suffered considerably from high-angle attenuation (which comes into play at sufficient distances), and were therefore not of great value for determining layer densities, but were particularly useful in hinting at the attenuation characteristics of the layers. The 16-m South African echo spreads are very irregular and show evidence of very considerable high-angle attenuation. This is especially marked on the midday signals and is illustrated in Fig. 5, which shows the maximum layer electronic density as a function of the time (G.M.T.). The ordinates giving density are of course uniform functions of the echo spread, so that a similar, but not quite uniform, vertical scale would give this quantity. The salient feature of this curve is the apparent dip in maximum density at a little after midday (1230 to 1240 G.M.T.) at a time when there is no doubt that the density should be a maximum. The decrease in echo spread at this time must be due to attenuation of the higher-angle rays. One point of particular interest is that the dip occurs at 1230 G.M.T., but the minimum signal strength (as determined by the diurnal signal curves) occurs throughout the year at between 1000 and 1100 G.M.T.

These results imply that the attenuation which cuts out the high-angle rays (as shown in the facsimile results) occurs in the F layer. The feature of this type of attenuation is the discrimination between high- and low-angle rays, the former being much more attenuated than the latter. The feature of E-layer attenuation is that it attenuates all shallow-angle rays practically equally.

It is therefore reasonable to attribute the attenuation observed in the facsimile results to F-layer attenuation, especially as it occurs at a time when the F-layer density is a maximum, i.e. about 1 hour and 40 minutes after the time of maximum density in the lower layer.

In comparing these South African results with the similar Montreal results in respect of maximum layer densities, only the maximum echo spreads should be taken into account. Comparing, then, the two echo spreads, they are approximately 0·95 millisecond in the case of Montreal and between 1·6 and 2·0 milliseconds in the case of South Africa. The ratio is, as it should be, approximately the ratio of the two distances from Somerton, England.

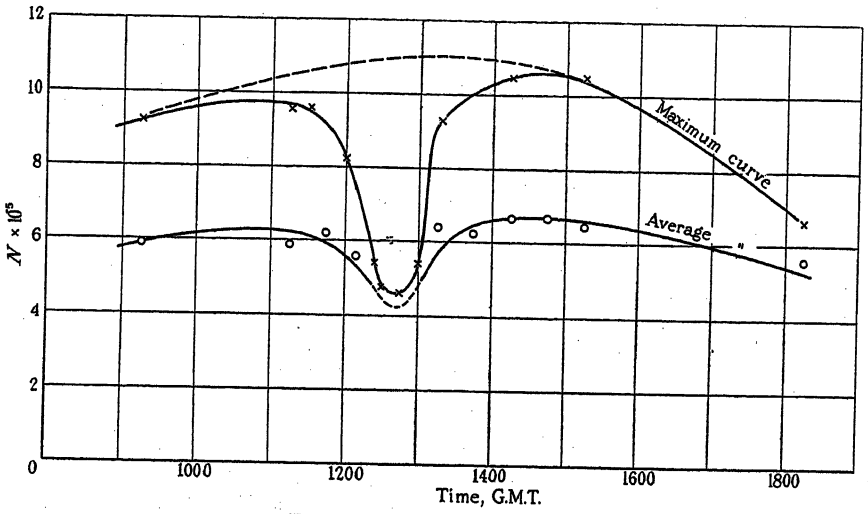


FIG. 5.—South African route.

These considerations are of great significance in long-distance facsimile work, for if there is greater attenuation on high-angle rays than on low-angle ones—as the evidence seems to suggest—then at sufficient distances only the lowest-angle ray will survive, and perfect facsimile will be possible. This suggests that long distances will be better than short ones for facsimile work. The fact recorded that round-the-world signals are free from short echo is naturally explained, as is also the observation common among traffic-handlers, that of the beam circuits Australia—the most distant—can be run at the highest speeds and is, in fact, freest from "signal spread" due to quick echo. To take practical advantage of this it would be necessary that the difference in attenuation of high- and low-angle rays should be so great that the higher-angle ray is reduced to negligible proportions before the lower-angle ray is reduced below noise-level, which conditions can be satisfied if the power-level at the transmitter is sufficiently increased.

Many of the records show very complex echo patterns, which vary from moment to moment. Others are much more regular and show consistent values of echo time which, on taking means, give values with small probable errors. In the case of South Africa (16 m) there is a type of irregular delay echo which, if computed in the ordinary way, would give excessive and irregular values of N [see Plate 2(3)]. On examining the records, these occasions seem to correspond to periods of magnetic storms. The author is inclined to attribute them to violent scattering which, from other evidence, seems to accompany magnetic disturbances. On the same lines he thinks it likely that the irregular echo patterns observed in normal transmission are due to more or less normal scattering.

Consider, for instance, a normal high-order ray represented by AA′ BB′ CC′ DD′ E . . . . 4th order (Fig. 6). If during the course the ray were diverted a few degrees into the direction of the next higher-order ray (the 5th, say), then this composite ray would arrive at a time intermediate between the 4th- and 5th-order normal rays. Reasons will be given later for supposing that small scattering deviations can occur without appreciable loss of energy, so that the final result will be a displaced echo. The rapid variation of such irregular echoes from time to time precludes the assumption that they are due to any regular horizontal gradient in the layer. The high-angle echoes disclosed by the 60-m and 120-m Writtle–Somerton facsimile tests are much more regular, a result which naturally follows from the fact that small-angle deviations of the ray paths in such a case make but little difference to the observed path.

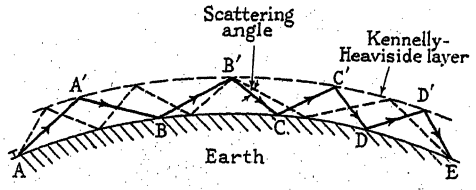


FIG. 6.

There is a record of Montreal taken during a magnetic storm, not sufficient to cut out all signals, but to reduce them very considerably below normal level. This is illustrated in Plate 2(4), which can be compared with Plate 2(1) showing the normal facsimile at this time. The magnetic-storm record is characterized by the almost complete absence of echo, and hence of high-angle rays.

If this is a normal storm condition it shows that signals are weakened by high-angle attenuation at such times, and hence, at least in the less severe cases, storms act chiefly by increasing the attenuation of the upper layer.

The most important information given by facsimile records can be obtained from the series of night records already referred to. The importance of these depends on the fact that after sunset, when, as presumed, the ionizing agent is removed, the reduction of the layer density is controlled almost entirely by recombination, so that density measures at this time should, if sufficiently accurate, give a precise measure of the electronic recombination coefficient undisturbed by other incalculable factors. The knowledge of the recombination coefficient plays a prominent part in our understanding of the behaviour of the Kennelly-Heaviside layer and in constructing an adequate model of it. The importance of the measurement of this quantity is not confined to its application to radio, for it is an essential physical constant which (under the condition in the Kennelly-Heaviside layer) it is impossible to measure in a laboratory. The results have therefore been very carefully analysed with a view to the determination of this quantity.

The greatest weight can be given to a set of records taken on Montreal during the night of the 10th–11th May, 1931. These comprise six records taken at the following times (G.M.T.):—2045, 2210, 2355, 0130, 0315, 0405.

Enlarged sections of the records are shown on Plate 1. It is easy to see at a glance how the echo time decreases as the night advances, showing the gradual decrease of maximum density in the F layer.

A large number of measurements were made, giving the times of the last echo, and any other echoes that were clearly defined. From the average echo delay for each record the corresponding maximum layer density was derived by the method already described.

The final results depend on the estimate of the time taken by the initial signal to traverse the path, or—what is essentially the same thing—the value of τ_0, the difference between this time and d/c.

Two values of τ_0 were used in determining alternative final results. The first value, $\tau_0 = 0{\cdot}17$ millisecond, was obtained by assuming that there were enough electrons in the E layer (at least during the initial part of the run) to hold down the initial ray. The second value of τ_0 was obtained on the assumption that even the lowest-angle ray penetrated the E layer, and travelled in conditions similar to the round-the-world echoes. In this case we can use the measurements of the time delays of these echoes to obtain a value of τ_0. Thus the results of Quäck, Taylor and Young, etc., can be applied.

In these results we have the measured value of the time taken by the echo to traverse the circumference of the world. We may express this as $(2\pi R_0/c) + \delta\tau$. $\delta\tau$ is the extra time taken by the pulse in encircling the globe, on account of the fact that when reflected to and fro between the earth and the Kennelly-Heaviside layer it travels at a mean radius greater than that of the earth.

From the available observations $\delta\tau$ does not appear to vary systematically with the wavelength. A mean weighted value of 4·7 milliseconds has been taken. From what has been said before about long-distance high-angle attenuation, it is clear that this time, added to $2\pi(R_0/c)$, is the time taken by a pulse on the *lowest*-angle ray to traverse the circumference of the earth.

If this quantity is reduced in the ratio of the Montreal–Somerton distance to that of the earth's circumference, we have a close approximation to the time of travel of the initial signal from Montreal to Somerton. The conditions on the round-the-world echo path and those on the Montreal–Somerton path are sufficiently alike to make such an assumption legitimate. The value of τ_0 is then 0·58 millisecond.

If the decrease in density in the F layer is conditioned wholly by recombination, as we assume, the progress with time can be determined from the recombination differential equation, which is

$$\frac{dN}{dt} = -\gamma N^2 \quad . \quad . \quad . \quad . \quad (22)$$

where γ is the recombination coefficient.

If N_s is the value of N at sunset (when pure recombination starts), then the solution of this equation gives

$$N = \frac{N_s}{1 + \gamma N_s t}$$

or

$$\frac{1}{N} = \frac{1}{N_s} + \gamma t \quad . \quad . \quad . \quad . \quad . \quad (23)$$

t being the time after sunset.

The relation between $1/N$ and t is linear, the slope of the line being the recombination coefficient and the intercept on the vertical axis at $t = 0$ being $1/N_s$.

Working the results out on the assumption that $\tau_0 = 0{\cdot}17$ millisecond, the first four points lie well along a straight line, but the last lies well above it.

It must be remembered that the last value of N is determined by a very shallow-angle ray, and little weight should be attached to it. If, however, we assume $\tau_0 = 0{\cdot}58$ for the last point (i.e. that the ray is no longer held down by the lower layer), all these fall well on a straight line giving the characteristics

$$N_s = 4{\cdot}5 \times 10^5 \text{ electrons per cm}^3$$
$$\gamma = 9{\cdot}3 \times 10^{-11}$$

which, of course, will also be the values obtained by neglecting the last point.

Using the alternative value $\tau_0 = 0{\cdot}58$ millisecond (which the author considers to be more probable), the values for N_s and γ are

$$N_s = 5{\cdot}2 \times 10^5 \text{ . . . . electrons per cm}^3$$
$$\gamma = 9{\cdot}5 \times 10^{-11}$$

The final results are, it will be seen, not very sensitive to change in τ_0, so that we may consider these values to be fairly well determined.

A record taken on the 9th April, 1931, at 1900 G.M.T. gave a large number of separated echoes, and assuming $\tau_0 = 0{\cdot}17$ there were definite echoes corresponding to $N = 4{\cdot}5 \times 10^5$ and a few to $N = 5{\cdot}2 \times 10^5$, with some evidence of an 8th-order reflection which, with $\tau_0 = 0{\cdot}58$, gives a value of $5{\cdot}7 \times 10^5$.

On a number of the records for Montreal (16 m) there

were some very faint, smudged, but still quite definite, echoes. They gave consistent values on measurement, and with $\tau_0 = 0{\cdot}58$ the density value was $9{\cdot}75 \times 10^5$. This value is considerably higher than that determined for 32 m. The results may be spurious, owing to the partial reflection of rays of greater than the critical angle, or they may be due to scattering. The normal 16-m Montreal echoes on records taken between 1900 and 2000 G.M.T. gave N values (assuming $\tau_0 = 0{\cdot}58$) equal to $6{\cdot}8 \times 10^5$, a more reasonable value.

At the same time as N was worked out, the effective heights were determined. There were hardly enough of these to give very reliable values, but the approximate values obtained for different ray orders are as follows:—

Order	Effective height
3	336 km
4	324 km
5	334 km
6	337 km
7	326 km

There appears to be no systematic variation with the ray order, as might at first sight be expected. With a graded layer the lower-order rays, with smaller angles of elevation, might be expected to give lower effective heights. In this connection, however, it must be remembered that the lower-order rays were measured later at night, when the density has everywhere decreased, so that the reduction in effective height of the ray on account of the lower order is probably compensated by an increase in effective height caused by a general thinning of the F layer.

The New York–Somerton facsimile results originally discussed in the author's "Multiple Signals in Short-Wave Transmission"* have been re-examined in the light of the more refined method of analysis. In particular a 24-hour run taken on the 21st and 22nd October, 1928, provides material for a nearly complete diurnal curve of N. Considering first the night records from which values of N_s and γ comparable with the recent Montreal values can be obtained, we have, as before, to decide on the possible alternative values for τ_0.

As in the case of Montreal, the alternative values correspond to the assumptions:—

(1) That the initial ray is held down by the E layer.
(2) That it penetrates this and that the echo delay is $d/(2\pi R_0)$ times the round-the-world echo delay.

These assumptions give for τ_0 the values:—

In case (1) 0·19.
In case (2) 0·635.

In working out the results with these two values of τ_0 it is found that the last value of $1/N$, which is always the least reliable, lies well off the straight line determined by the other points. In the following calculations it is therefore neglected.

Assuming $\tau_0 = 0{\cdot}19$ and rejecting the last point, we get

$$N_s = 6{\cdot}1 \times 10^5 \quad \text{and} \quad \gamma = 5{\cdot}92 \times 10^{-11}$$

* *Loc. cit.*

Assuming $\tau_0 = 0{\cdot}635$ and rejecting the last point, we get

$$N_s = 11 \times 10^5 \quad \text{and} \quad \gamma = 6{\cdot}7 \times 10^{-11}$$

Of the two pairs of values the last seem to the author to be much more probable. The points are rather scattered, and the results are probably less reliable than the Montreal ones.

The New York–Somerton results provide more material for the estimation of the equivalent heights, and there are enough values to enable the probable errors to be worked out.

The results are recorded in Tables 1 to 3. Assume first that $\tau_0 = 0{\cdot}19$.

TABLE 1.

$\tau = 0{\cdot}19$.

n	h	Number of readings
	km	
2	$293 \pm 15{\cdot}7$	8
3	$307 \pm 19{\cdot}7$	13
4	$330 \pm 15{\cdot}1$	9
5	$338 \pm 7{\cdot}4$	3

Assuming that $\tau_0 = 0{\cdot}635$ millisecond, there is some uncertainty in the order of reflection involved, and it is possible to work out consistent values, one favouring lower values of height and the other higher values.

TABLE 2.

$\tau_0 = 0{\cdot}635$ *Favouring Low Values.*

n	h	Number of readings
	km	
3	$286 \pm 11{\cdot}6$	9
4	$287 \pm 10{\cdot}8$	12
5	$296 \pm 11{\cdot}4$	9
6	$303 \pm 4{\cdot}4$	3

TABLE 3.

$\tau_0 = 0{\cdot}635$ *Favouring High Values.*

n	h	Number of readings
	km	
2	$359 \pm 5{\cdot}6$	2
3	318 ± 20	13
4	$323 \pm 16{\cdot}2$	11
5	$320 \pm 11{\cdot}8$	5
6	$308 \pm 1{\cdot}6$	2

Of these three tables 1 and 2 show a systematic increase of h with n, as is expected from general theoretical considerations. Of the last two, with $\tau_0 = 0{\cdot}635$, the first seems much more likely, not only from the consideration of the systematic increase of h with n,

but also from the point of view of the smallness and evenness of the probable errors. In this respect it is even better than the table for 0·19 millisecond, and it is probable that, with a wavelength of 22 m, the higher value for τ_0 is the true value, except possibly for small-order rays in the daytime.

The other echo times taken during daytime contribute towards a determination of the complete diurnal curve of N. The values are represented in Fig. 7. The specification of the local time to which a given observation belongs offers a little difficulty. In east and west transmission the maximum density varies along the path. Consider, for instance, the case where it is some time after sunset at the eastern end (Somerton) but where the sun has not set at the western end. Although the density at New York is great and can reflect high-angle rays, these would escape through the F layer in the regions of less density between, near Somerton. The highest-angle transmitted ray depends on the region of maximum density near Somerton.

In general an observation must be associated with the local time at the region where the density along the path is a minimum. Now during a 24-hour period the region of minimum density shifts from one end of the path to the other. Thus in the New York–Somerton transmission, that region is at the eastern end after sunset and remains there until after sunrise, when the western end will be still in darkness and the region of minimum density will shift to the western end. This condition remains until well after midday between the two stations. The change-over point is not sharply defined, but this does not matter greatly because at the change-over point the densities are equal at both ends and the observations can be attributed to either end with equal legitimacy. For this reason, it will be noted, the values of the maximum density a little after midday cannot be observed, for wherever the point of maximum density may be on the path, there will be other points of less density on the path which will determine the maximum ray angle. North and south transmission in the neighbourhood of the equinoxes would avoid this trouble. In Fig. 7 the points have been corrected for this shift of local time.

The curve is very similar to that obtained by S. Chapman* for the variation of ionization produced by the monochromatic radiation from the sun. It will be seen later that his value $\sigma_0 = 0{\cdot}5$ (which leads to the curve that fits best) implies a recombination coefficient close to the value determined here. For comparison the part of the diurnal curve obtained for Montreal at night is sketched in. The full part is the observed region, while the dotted part is drawn in theoretically to fit this curve at sunset and is derived by the methods explained by S. Chapman in his paper. It lies wholly below the 22-m curve taken in October, 1928, although it is taken during May, 1931, when, with a given intensity of sun's radiation, the curve should lie wholly above A. This result seems to indicate a very considerable secular reduction in ionic densities during the period 1928–1931, caused by a reduction in the sun's ionizing agency, i.e. ultra-violet light. This is in accordance with many other radio observations, in particular those which indicate that a longer wave is necessary, for a given night communication in 1931, than that required in 1928.

The South African results, although the most numerous, are the least definite and conclusive. The length of the route and consequent overlapping of echoes, the varying conditions along the route (making high-angle absorption probable), and the large amount of extrapolation required to deduce the sunset value of N_s, combine to make the results very uncertain.

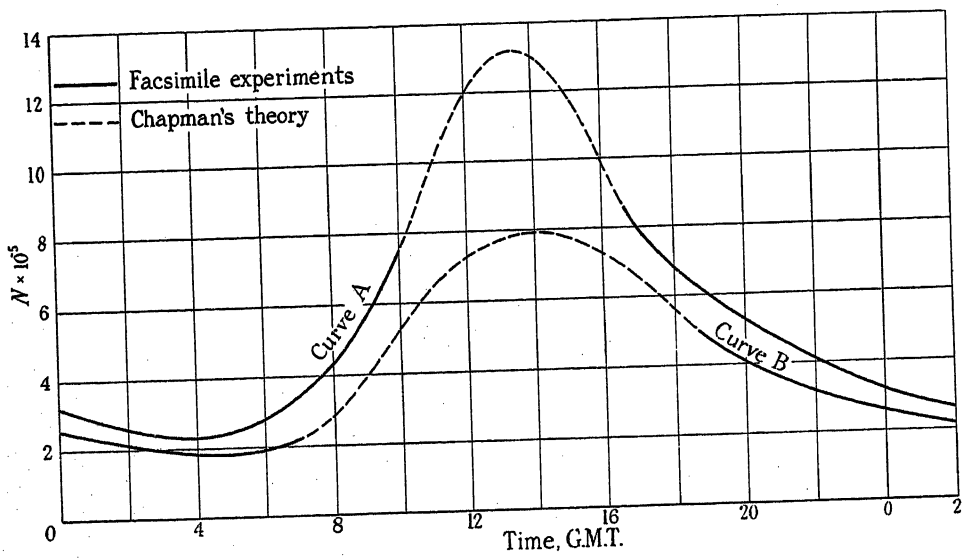


FIG. 7.

Curve A.—New York–Somerton. 21st–22nd October, 1928; $\delta = -11°$; latitude $= 45°$; $I_0 = 317$; $\alpha = 7 \times 10^{-11}$; $\sigma_0 = 0{\cdot}495$; $n_0 = 21{\cdot}3 \times 10^5$.

Curve B.—Montreal–Somerton. 10th–11th May, 1931; $\delta = +17° 45'$; latitude $= 45°$; $I_0 = 80$; $\alpha = 10^{-10}$; $\sigma = 0{\cdot}816$; $n_0 = 8{\cdot}94 \times 10^5$.

* *Proceedings of the Physical Society of London*, 1931, vol. 43, p. 26.

The records also show a large variation of density from day to day. There was, however, one night run, 21st–22nd May, 1931, which gave a set of six actual echoes spaced over a period of about 4 hours. The wavelength being 32·7 m and the path being over equatorial regions, the lowest ray may possibly have been held down by the E layer.

Taking, in consequence, $\tau_0 = 0 \cdot 34$, the following values for N_s and γ were determined:—

$$N_s = 3 \cdot 8 \times 10^5 \text{ electrons per cm}^3$$
$$\gamma = 8 \cdot 1 \times 10^{-11}$$

If, however, we assume $\tau_0 = 1 \cdot 14$, implying that the initial ray penetrates the lower E layer, then the values are:—

$$N_s = 3 \cdot 58 \times 10^5 \text{ electrons per cm}^3$$
$$\gamma = 4 \cdot 25 \times 10^{-11}$$

The uncertainty is shown up by the divergence of the results, and not much reliance should be placed on them.

layer is a maximum. This is the time at which the sun's mean angular elevation is a maximum on the route. At 1245 G.M.T., about 1 hour 20 min. later, the F layer is at a maximum. The lag of $1\frac{1}{2}$ hours or so after the sun's maximum elevation is a consequence of the slow recombination in the F layer. These measurements give very indefinite estimates of the equivalent height of the F layer, owing to the difficulty in deciding the order of the reflection involved, and there is insufficient evidence to decide between values of 250 and 350 km.

The final set of facsimile measurements to be discussed are those made on 60 and 120 m on the 14th–15th February and the 21st–22nd February, 1930, between Writtle (near Chelmsford) and Somerton, a distance of 227 km. These tests show most conspicuously the existence of three or even four definite, regularly-spaced echoes, which, on measurement, appear almost conclusively to be caused by multiple reflection between the earth and a well-defined region of the Kennelly-Heaviside layer at a height of between 180 to 280 km

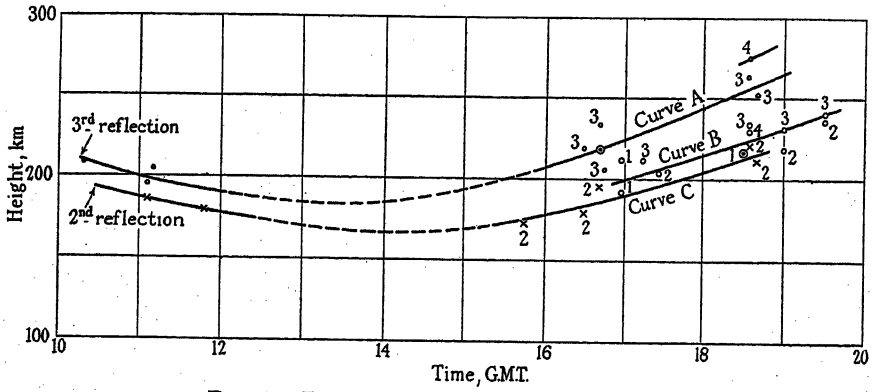


FIG. 8.—Equivalent height of Heaviside layer.

Curve A.—60-m test.
Curve B.—120-m test (22nd–23rd Feb.).
Curve C.—60-m test (15th–16th Feb.).

The long series of records on 16 m (Fig. 5), which have already been referred to, showed no individual echoes, but by measuring the overall length of the image and subtracting the estimated (and measured) length of a single pulse, a curve was obtained giving the variation of density with G.M.T. over the range 1100 to 1530 G.M.T., with isolated points at 0915 and 1815 G.M.T. The experimental points, about 200 in all, are very widely scattered, and in the author's opinion show the effect of high-angle attenuation, and therefore give a lower limit to the maximum density in the Kennelly-Heaviside layer.

The average curve shows a mean (N max.) density of $6 \cdot 5 \times 10^5$, and the upper limiting curve ABC shows densities up to $9 \cdot 3 \times 10^5$ (assuming $\tau_0 = 1 \cdot 14$). It also shows a very marked dip at 1245 G.M.T. This dip is, without doubt, due to high-angle attenuation at the times when the density in the F layer is a maximum, and is not due to attenuation in the E layer, which produces its maximum effect (as shown from the signal-intensity curves) at between 1000 and 1100 G.M.T., at which time the density in the lower (lower part of the F layer)—depending on the time of the day. On 120 m in the daytime the long delay echoes of 2 milliseconds or more were completely absent, and although the remaining signal was obviously composite and faded, the speed was not sufficient to separate the components. The longer echo appeared to start between 1715 and 1725 G.M.T. (sunset 1726 G.M.T.). It is interesting to note that the signal strength increased above its mean day value at a period considerably earlier (about 1630 G.M.T.) than the time at which the long delay echo first started.

On 60 m during the daytime, echoes of delay greater than 2 milliseconds were generally present, except for a period about midday on Sunday, 5th February, when the echoes were either absent or too weak to record.

The initial signal was clearer and better defined on 60 m than on 120 m. The day signal also appeared to be stronger on the former, but this may have been an effect due to decreased noise-level. There was not much change of the average signal strength between day and night on 60 m, but there was a large increase on 120 m.

On 60 m at night there was a very definite " smudging "

of the signals [illustrated on Plate 2(5)] which in some cases lasted up to 20 milliseconds after the first signal. The author has little doubt that this effect is due to "scattering," which is a very marked characteristic of directional measurements made at this distance. This scattering effect was very much less marked on 120 m than on 60 m.

The equivalent heights for the definite multiple echoes are shown in Fig. 8, where the heights are plotted as a function of the time of the day.

Angles of elevation up to 84° are observed, showing that the F layer is sufficiently dense to reflect even at normal incidence. The density must therefore be greater than 2×10^5.

The curve of equivalent height (for nearly vertical rays) reaches a minimum at about 1330 to 1400 G.M.T., of about 200 km, and rises fairly rapidly to nearly 280 km at 1900 G.M.T. The drop from 1000 G.M.T. to 1300 G.M.T. is less steep. The points marked with a cross are taken from Kenrick and Jen's paper,* and represent the measured effective height of the F layer about the same time (February, 1929) the year before. The agreement is very close.

The reflection of the lower-angle rays (second reflection) is at a lower equivalent height than that of the higher-angle rays, indicating a fairly shallow gradient for these densities, i.e. about 3×10^5.

A remarkable feature is the apparent absence of single-reflection rays. These would have only about 0·6 to 0·7 millisecond delay, and the speed of the drum is insufficient to separate them very clearly from the direct signal.

There is evidence, however, of rays delayed about this amount in the early evening at 1830 G.M.T. on the 14th February. In these pictures a series of bars $\frac{1}{16}$ in. wide were transmitted. These are reproduced as a series of bars with a longish echo (probably third reflection but rather too irregular to measure). The bars are cut up by interference signals, some of which start almost simultaneously with the first signal, and some of which start about 0·688 sec. later (corresponding to a reflection equivalent height of 216 km for single reflection).

In the daytime there is no certain evidence of this single reflection.

The angle of elevation for such rays would be approximately 60°. Now the 100-km E layer is known to have a maximum density of about from 1 to 2×10^5, for which the critical angle is 35° to 60° (nearly.)

After night-fall, when the density in the E layer is reduced (as well as the attenuation), such first-order rays may appear as in the example cited.

Scattering.

Scattering is shown in many of the illustrations, and is particularly intense on 60 m after sunset. The fact that in certain cases the scattered signal lasts for 20 milliseconds after the original signal has arrived, implies an increase of path of the scattered signal of 6 000 km in extreme cases. The average scatter is of the order of 10 to 12 milliseconds, representing a scattering source from 1 500 to 1 800 km distance. This agrees approximately with the distance obtained by triangulating the scatter source of the beams, the average distance being 1 930 km for a shorter average wavelength.* If bars are transmitted, the scattering is exhibited on the received reproduction as somewhat ragged tails lasting up to 10–20 milliseconds. By tracing these smudges back to where they interfere with the direct initial signal, it appears that the start of the scatter signal is from 0 to 0·7 millisecond later than the direct signal. The recorder velocity was not great enough to determine the lower limit accurately. It would therefore appear probable that the scattering originates in the region between the E and F layers. It is unlikely to occur lower than the E layer, for when the regions above this are shielded by the attenuation in this layer there is little or no appreciable scattering. The irregular incidence of the scatter signal, the variations between day and night, the reduction of scattering with wavelength, and the presence of scattering from regions over the sea, where, as mathematical analysis shows, it is only in exceptionally rough conditions that any appreciable surface scattering can occur, seem to make it very probable that the scattering occurs in the Heaviside layer and not, in the main, from irregular objects on the earth's surface.

The pictures show that the general level of the scatter intensity is usually less than that of the main or echo signals, and it is rather irregular in incidence.

The phase of the scattered signal relative to the direct signal appears to remain constant over periods of the order of 0·05 second, as shown by the duration of the interference between direct and scattered signal, so that a snapshot determination of direction, if it could be made in such a short interval, would give a momentarily definite direction of energy-travel.

120-*m Tests*.

The results of these tests are similar in most respects to the 60-m results, except that in this case there is practically no measurable echo in the daytime, and very little sign of scattering.

Day signals on Saturday, the 22nd, and Sunday, the 23rd February, are certainly multiple, since they fade, but the echo was too close to the main signal to measure accurately.

It will be observed that the second- and third-order echoes on 120 m give equivalent heights (between 1600 and 1930 G.M.T.) very close to the second-order signal on 60 m. Thus the measured equivalent heights on 60 m and 120 m appear to differ very little, and the results therefore suggest at first sight a rather sharply defined layer at this height. It must be remembered, however, that the longer wavelength (120 m) is much more delayed in the regions of the lower layer—Appleton's E layer—than is the 60-m wave, so that part of the observed equivalent height on the 120-m wave is due to the slow passage of this wave through the E layer, and it is impossible to infer from the results how sharp is the gradient at the F layer. The delay on the 120-m ray in passing through the E layer may be inferred from our knowledge of the density of this layer. In fact it is rather surprising that it penetrates it at all, for this would be impossible if we were to take the

* *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 2034.

* *Journal I.E.E.*, 1929, vol. 67, p. 997.

usually accepted figure of 10^5 for the maximum density in the layer.

Such a layer would be over-dense, and would allow no penetration at all on this wavelength. We must suppose that at such times as the longer echoes were observed (early morning and evening), the E layer has not reached its normal value of 10^5 and must be less than $0{\cdot}705 \times 10^5$. The delay suffered by this 120-m ray in the lower layer will depend on the closeness of N to this critical value.

Reflections from E Layer.

While the evidence as regards the F layer is very clear and definite, that with respect to the E layer is very confused. One fact, however, is quite definite: in the daytime the lower layer is so attenuating (and possibly so dense) that no 120-m ray survives the passage through it to the upper layer and down again. There is evidence, however, that some energy is reflected from the E layer and produces fading and interference.

The delay which a ray reflected at the equivalent height of 100 km would suffer is 0·25 millisecond. This is rather too short an interval to be clearly shown on the records with a scanning speed of 30 in. per sec. (used in all the experiments), but although there was a series of echoes from 0·5 to 0·8 delay at most times in the evenings on the 120-m test and also (observed as interference) in the 60-m test, there are none of 0·25 millisecond delay, as far as could be observed. The 0·5–0·8 millisecond delay signal might be produced by rays bent at the E layer. The equivalent height would then be very large compared with the actual height (i.e. about 100 km).

Such a state of affairs occurs when the appropriate ray nearly penetrates the E layer, for in such conditions the ray is one which starts up steeply, traverses nearly horizontally in the layer, and comes down steeply again. It is clear from the geometry that in such a case the equivalent height is large compared with the actual height. Higher scanning speeds would be necessary to obtain clear evidence on this point.

Constitution and Behaviour of F Layer.

These facsimile results have a very significant bearing on the theory of the constitution of the F layer. This theory has been discussed very fully recently by S. Chapman in his Bakerian Lecture before the Royal Society, and it is interesting to see how far the results agree with his conclusions.

Taking our results, let us see what can be deduced. Let us first consider the run of the night densities. These, according to our measurements, fall off in a regular manner from sunset to dawn. On the assumption that this reduction is due to the recombination of the electrons with atoms of one species, the relation between $1/N$ and t, the time after sunset, should be a linear one. If there were more than one type of recombination, or more than one species of atom taking part in this process with widely different recombination coefficients, the curve would no longer be linear. The actual results, as far as their accuracy will allow, suggest a purely linear relation, and therefore a preponderance of one type of reaction.

We can also infer that after sunset the density behaves as if the ionizing agent were removed, and that the layer settles down towards equilibrium by recombination. If there is a residual ionizing agent during the night, it appears to be small at these and lower latitudes and in normal conditions.

The determinations of the recombination coefficient give fairly widely differing values, i.e. $9{\cdot}3 \times 10^{-11}$, $9{\cdot}5 \times 10^{-11}$, $6{\cdot}7 \times 10^{-11}$, $5{\cdot}1 \times 10^{-11}$, and $4{\cdot}25 \times 10^{-11}$, of which the first two have by far the greatest weight and the last two very little weight, so that for a weighted mean we can take the value of 9×10^{-11}.

From the diurnal N curve (obtained in 1928 on 22-m facsimile) it appears that the ionizing agency starts about sunrise and ceases about sunset. This would be naturally accounted for if we assume that the ionizing agent is the sun's ultra-violet radiation, or at least some agency which is propagated from the sun in straight lines. There is strong theoretical reason for believing that the sun, which to all intents and purposes acts as a black-body radiator, would actually emit enough ultra-violet radiation to ionize the upper atmosphere in suitable conditions.*

On this assumption, measurements of the effective height of the F layer allow us to make some further deductions.

Thus, the effective height as measured must exceed the height of the apex of the limiting ray, where N has its maximum value. It is also almost certainly above the apex of the equivalent ray for 60 m in daytime. Thus we may consider the density in the F layer to be a maximum between 200 km and 300 km.

Now in the simplified theory discussed by S. Chapman, the height at which N is a maximum has a definite physical significance, and is determined by the absorption coefficient of the ultra-violet rays, the quantity H (the height of the homogeneous atmosphere of the absorbing atoms or molecules), and the molecular density at a given datum. For at the time when the density at midday is a maximum in an approximately steady state, the recombination equation gives

$$\frac{dN}{dt} - \gamma N^2 = I \quad . \quad . \quad . \quad . \quad (24)$$

where I is the rate of production of ions.

If now dN/dt is zero at all heights at the midday maximum of N

$$N = \sqrt{\frac{I}{\gamma}}$$

i.e. N is a maximum in the same region as I is a maximum. But I can be expressed in the form

$$I = \beta\rho_0 S_0 e^{-\frac{z}{H} - H\gamma\rho_0 \sec\theta \exp\frac{-z}{H}} \quad . \quad . \quad (25)$$

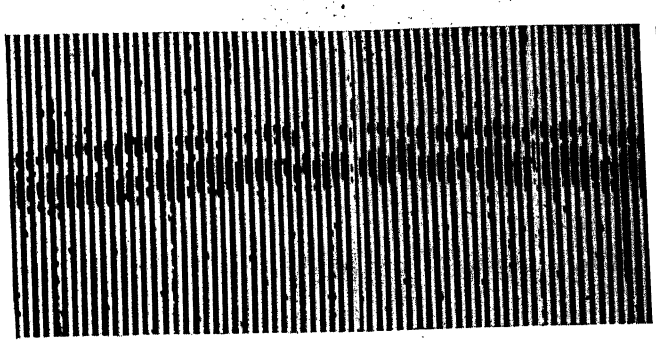
in which it is assumed that at a height Z the molecular density

$$\rho = \rho_0 e^{-Z/H} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

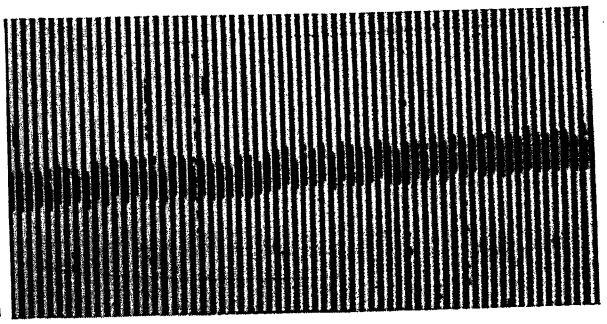
β is the absorption coefficient for the radiation of

* Chapman quotes the observations of C. Fabry and H. Buisson, *Mémorials des Sciences Physiques*, pt. II, ch. 3 (Gauthier-Villars, Paris, 1930).

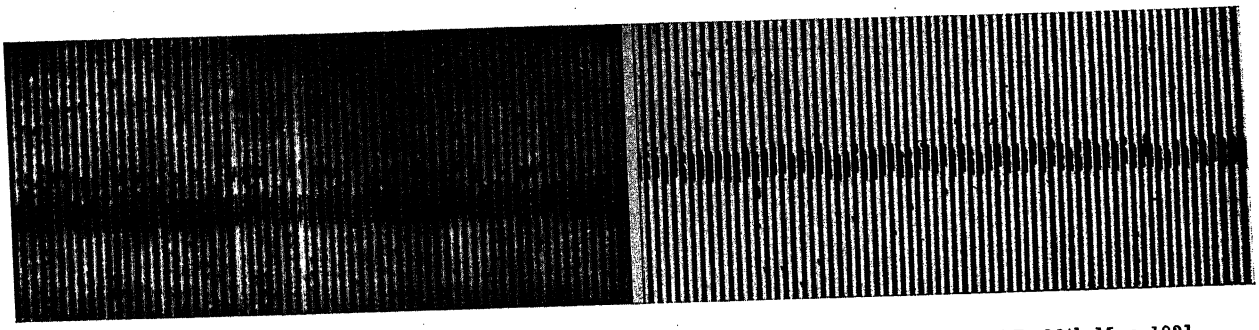
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(1) Montreal (32 m). 2045 G.M.T., 10th May, 1921.
Scanning speed 57·6 in. per sec.

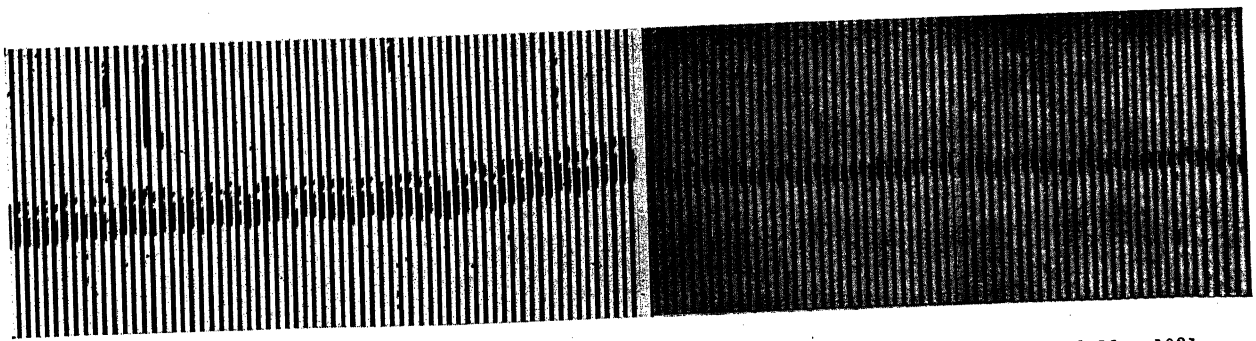


(4) Montreal (32 m). 0130 G.M.T., 11th May, 1931.
Scanning speed 57·6 in. per sec.



(2) Montreal (32 m). 2210 G.M.T., 10th May, 1931.
Scanning speed 57·6 in. per sec.

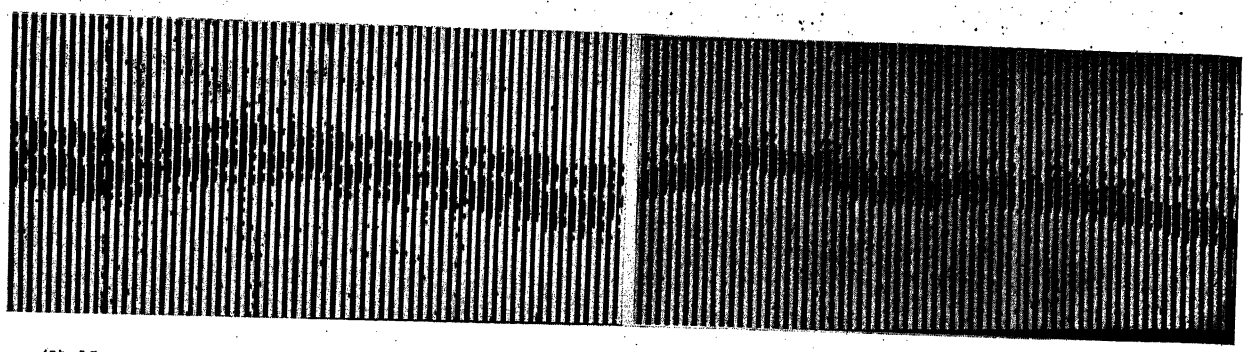
(5) Montreal (32 m). 0315 G.M.T., 11th May, 1931.
Scanning speed 57·6 in. per sec.



(3) Montreal (32 m). 2355 G.M.T., 10th May, 1931
Scanning speed 57·6 in. per sec.

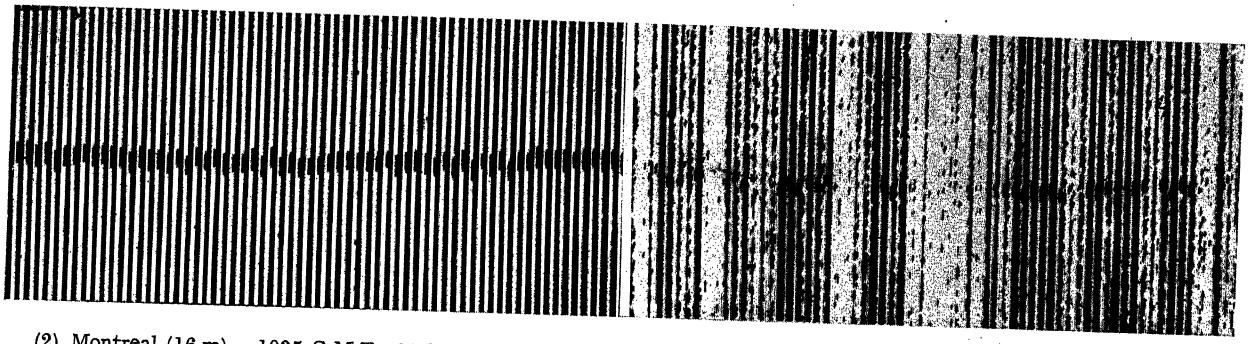
(6) Montreal (32 m). 0405 G.M.T., 11th May, 1931.
Scanning speed 57·6 in. per sec.

Plate 2.



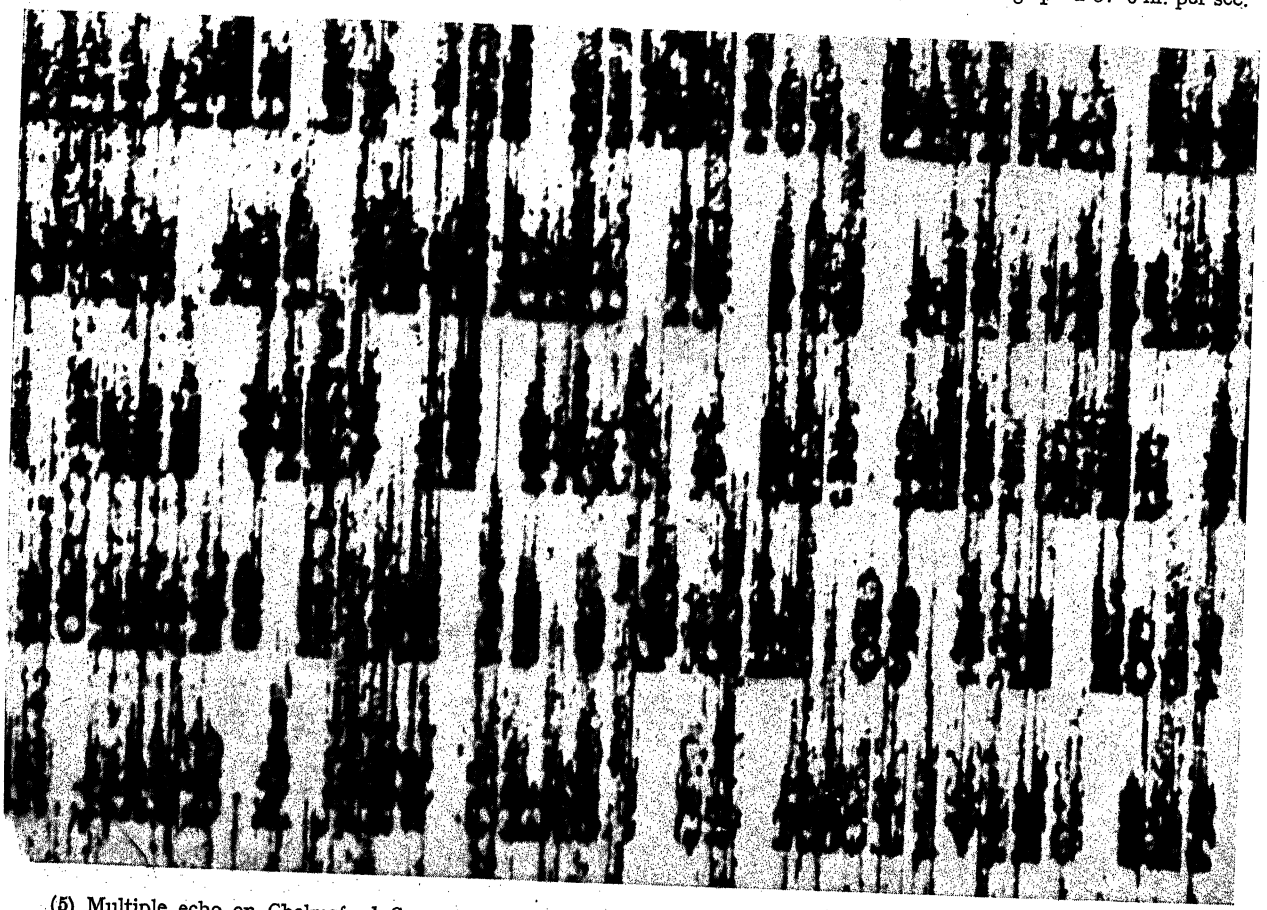
(1) Montreal (32 m). 1915 G.M T., 13th May, 1931. Scanning speed 57·6 in. per sec.

(3) South Africa (16 m). 0920 G.M.T., 2nd June, 1931. Scanning speed 57·6 in. per sec.



(2) Montreal (16 m). 1935 G.M.T., 29th June, 1931. Scanning speed, 57·6 in. per sec.

(4) Montreal (32 m). 1905 G.M.T., 15th May, 1931 (magnetically disturbed day). Scanning speed 57·6 in. per sec.



(5) Multiple echo on Chelmsford–Somerton route. Wavelength 60 m. Time 1820 G.M.T., 15th February, 1930. Very marked scattering. Scanning speed 30 in. per sec.

intensity S, and θ is the zenith distance of the sun at this time.

I, and therefore N, are a maximum at a height given by $dI/dZ = 0$. This gives

$$Z = -H \log \frac{1}{H\rho_0\beta} - H \log \sec \theta \quad . \quad . \quad (27)$$

so that the absorption coefficient β can be determined when H and ρ_0 are known.

Unfortunately we cannot proceed deductively on these lines any further, for there is no direct evidence of the nature of the absorbing atom or molecule, and even if there were we cannot definitely specify either H or ρ_0, which depend on some initial assumption.

S. Chapman has, however, developed a possible theory of the F layer in which its main features can be reproduced without the use of any disposable constant. It is important, therefore, to see whether our further information confirms his theory or not.

In his theory the ionizing agent for the F layer is considered to be the sun's ultra-violet radiation. The conclusion derived from our diurnal N curve, which indicates the presence of an ionizing agent only during the day period, is in full accord with this assumption.

By consideration of the dissociation of molecular oxygen and ozone in the layer at a height of 50 km, by different bands of the sun's radiation he shows that the ratio of atomic oxygen to molecular oxygen increases upwards without limit (above the ozone layer height). For this reason atomic oxygen will be one of the main constituents of the earth's atmosphere at great heights.

Consider now the ionization. Apart from dissociation, the energy needed to ionize one of the species of atom or molecule, measured in volts, is shown in Table 4 (given by S. Chapman).

TABLE 4.

Molecule or atom	Volts	Ionization wavelength	Number of quanta
O	13·6	910	7×10^8
O_2	16·1	770	8×10^6
H_2	16·1	770	
N_2	16·9	730	2×10^6
He	23·5	490	0·3

The last column gives the number of quanta of the required (or greater) energy available per cm^2 in the sun's radiation, when the sun is in the zenith at the place considered.

Atomic oxygen is the most easily ionized, and the available energy for this process is the greatest.

In view of these data, it is considered that the main contributor to the ionization is atomic oxygen. If this is the case, the recombination coefficient should be appropriate to the recombination of electrons and atomic oxygen. In this connection we may again quote S. Chapman. "Asssuming that ions and electrons combine only with one another, Milne's theory gives for the recombination coefficient γ a formula which, omitting certain factors of the order unity, is

$$\gamma = \frac{32\pi}{3}\left(\frac{2\pi me}{3K}\right)^{1/2} \frac{Z^2e^6\nu_0}{c^3m^2h\nu T^{1/2}} \quad . \quad . \quad (28)$$

where m denotes the electronic mass, $K = 1{\cdot}37 \times 10^{-16}$, h is Planck's constant $= 6{\cdot}55 \times 10^{-27}$ C.G.S. units, and T denotes the temperature of the gas. For atomic oxygen, taking the atomic number $Z = 8$, $T = 300°$ or $T = 400°$, we find that γ is $3{\cdot}7 \times 10^{-10}$ or $3{\cdot}2 \times 10^{-11}$, the dependence on T not being very important. The uncertainty as to the factor Z^2 affects γ and β equally (β being the absorption coefficient); if $Z^2 = 25$ (as possible) instead of 64, γ must be reduced to $1{\cdot}5 \times 10^{-10}$ or $1{\cdot}3 \times 10^{-10}$."

The actual value of γ found in our experiments, i.e. $0{\cdot}9 \times 10^{-10}$, is in good accord, considering the various uncertainties with the theoretical and observed results, and may be considered to provide strong confirmation.

On making a reasonable assumption as regards the atomic oxygen concentration and its distribution according to Dalton's law, Chapman finally arrives at the conclusion that the electronic density N has its maximum value of 4 to 6×10^6 at a height a little over 200 km. The values of $N_{max.}$ are rather high compared with our measured values, and the height possibly a little low, but the uncertainty of the data does not allow of a more precise determination of these factors, and there is no evidence that can be considered inconsistent with the theory. Although other possibilities are not definitely ruled out, there is a very strong presumption in favour of this theory.

The facsimile experiments give very little information in regard to the E layer. The frequencies dealt with are so high that the relatively small electronic densities in this layer have but little effect on their transmission. Prof. Appleton has made a very complete investigation of this layer, and the theoretical aspect of his results has been discussed by S. Chapman.

With regard to the ionizing agent, Chapman favours the hypothesis that it consists of ionized or neutral atoms which ionize the upper atmosphere by impact. A more or less neutral stream must be supposed, since the ionization is confined to the daytime, and the radiation or stream of atoms must proceed in straight lines from the sun. If this stream were not neutral it would be bent into the night regions by the earth's magnetic field. Milne's theory of the corpuscular emission from the sun fits this hypothesis well. The atoms likely to be emitted from the sun are those which have strong absorption bands in the solar spectrum. Some of these are ionized and some neutral. Milne has shown that both types acquire speeds of the same order of magnitude under the accelerating influence of the sun's radiation pressure—speeds which are sufficient to ionize the molecules and atoms in the E layer. The alternative hypothesis, that the ionizing agent is electromagnetic radiation from the sun, requires a very penetrating radiation of the X-ray type.

Using the same argument as before, in which the

mass absorption coefficient of the ionizing radiation is related to the region of maximum ionization, i.e.

$$z_{max.} = \log \frac{1}{H\rho_0\beta} \quad . \quad . \quad . \quad . \quad (29)$$

H and ρ_0 are fairly well determined, so that β, the mass absorption coefficient, can be found. It is $1{\cdot}37 \times 10^2$ and corresponds to the absorption coefficient of X-rays of 3·7 Å.U. in air. Such a radiation from the sun of sufficient quantity, though not inconceivable, is at least very improbable, and this alternative is very unlikely. The constants of the E layer which most affect radio transmission are (1) the maximum density in the layer, (2) the gradient of density (on the lower side), and (3) the collision frequency at various points in the layer.

With regard to (1), Appleton has recently published results* giving determinations of this quantity. The method used is similar to the facsimile method, but he uses nearly vertical rays and determines the critical frequency at which the rays penetrate the lower layer. Using a relation similar to equation (3) the value of $N_{max.}$ can be found.

Appleton's results may be quoted to the effect that for daytime in midwinter over southern England the value of N reaches 2×10^5 electrons per cm^3 at noon, after which the value falls steadily and remains at the low value of 3×10^4 during the greater part of the night. About half an hour before sunrise a very sharp increase is noted, after which the ionization increases more gradually until the maximum midday value is again reached. The diurnal variation curves bear a pronounced resemblance to the theoretical curves deduced by Prof. S. Chapman.†

With this value for $N_{max.}$ in the E layer during the night-runs it is probable that the 32-m or 33·7-m glancing rays will penetrate this layer, and that the larger value of τ_0 is appropriate for the night-runs on Montreal and South Africa.

The gradient of density in this layer no doubt alters from time to time. A series of measurements made by Appleton have given a representative value which the present author has found most useful in theoretical application. This is published in the *Proceedings of the Physical Society of London* (1930, vol. 42), in which in Fig. 5, page 336, he gives the variation of equivalent height with frequency.

The results were taken during a period of 2 hours after ground sunrise, when the layer-level is most constant.

The results show, in the present author's opinion, a very nearly linear increase of effective height with frequency, implying a nearly square-law increase in density (except, of course, in regions where N is a maximum). Although, of course, distribution may vary from time to time, the results provide a good working model.

Finally, let us consider the collision frequency. Table 5 is given by S. Chapman, and is based on the most recent determination of the temperature and density in the regions of the E layer.

These results should be sufficient to determine the approximate behaviour of short waves penetrating the E layer, and longer waves reflected or refracted by it.

Returning to the F layer again, it will be observed that we have attempted no determination of the layer gradients or distribution of N in the layer. The measured values of effective height are not sufficiently accurate for this purpose. It is perhaps rather remarkable that with the waves in the range between, say, 45 and 100 m, we obtain effective heights clustering round the value of about 210 to 220 km, while with shorter waves, 22–30 m, the effective-height measurements cluster round the value 300 to 340 km.

It is, of course, natural that the effective height should increase with increasing frequency, but the change between 45 m and 30 m seems rather abrupt, whereas the changes within the two separate bands 45–100 m and 20–30 m seem small. This is rather akin to the abrupt change at 100 m or so from the lower E layer to the F layer, and suggests the possibility of three layers. Without being too definite, we might possibly make the following suggestion:—The F layer appears in the main to be produced by the ionization of atomic oxygen by the ultra-violet band between 910 and 770 Å.U.

It is not entirely inconsistent with both the evidence cited above and the theory, that a secondary ionized layer with a maximum density of approximately one-third that in the F layer is produced at a lower level by the more penetrating radiation of about 770 Å.U. which ionizes molecular oxygen O_2, or 730 Å.U. which ionizes molecular nitrogen N_2. The two layers, as illustrated in Fig. 9, will overlap, producing a composite layer with a sort of shelf at C.

The lower-frequency radio waves would then be refracted at the rather sharply defined regions A, and the higher-frequency waves at B. This conclusion, though speculative, is not entirely unreasonable.

In accounting for the distribution of N into two layers we are burdened with the necessity of accounting for the absence of intermediate layers. This may be attributed to the lack of sufficiently intense radiation of requisite frequency. The amount available is shown in the last column of S. Chapman's table, and decreases rapidly with increasing frequency, but is not inconsistent

TABLE 5.

Height (km)	70	80	90	100	110	120	130	140	150
Collision frequency	10^7	$3{\cdot}3\times10^6$	$1{\cdot}1\times10^6$	$3{\cdot}5\times10^5$	$1{\cdot}2\times10^5$	$3{\cdot}8\times10^4$	$1{\cdot}3\times10^4$	$4{\cdot}4\times10^3$	$1{\cdot}5\times10^3$

* *Nature*, 1931, vol. 127, p. 197.
† *Proceedings of the Physical Society of London*, 1931, vol. 43, p. 26.

with a small secondary layer of ionized molecular oxygen or nitrogen.

Before leaving the discussion of the F-layer gradient, we may point out what may at first sight appear to be a serious omission in our simplified picture of the ray geometry. We have assumed, in effect, that there is only one ray of a given order which joins transmitter and receiver.

The author thinks that it was first pointed out by Baker and Rice that in general where wavelengths are used which can penetrate the upper layer, and where for some angle θ_1. As the angle of elevation is still further increased from θ_1 to θ_0, the critical angle, the target position passes outward again until at θ_0 the ray escapes and finds no target on the earth.

In general, therefore, for any fixed distance R, there is one ray of angle of elevation between O and θ_1, which finds its target at R_1, and another between θ_1 and θ_0 which also finds a target at the same point.

In general there are two first-order rays which reach R. In order to get more precise information as to the behaviour of the two rays, the author has used the

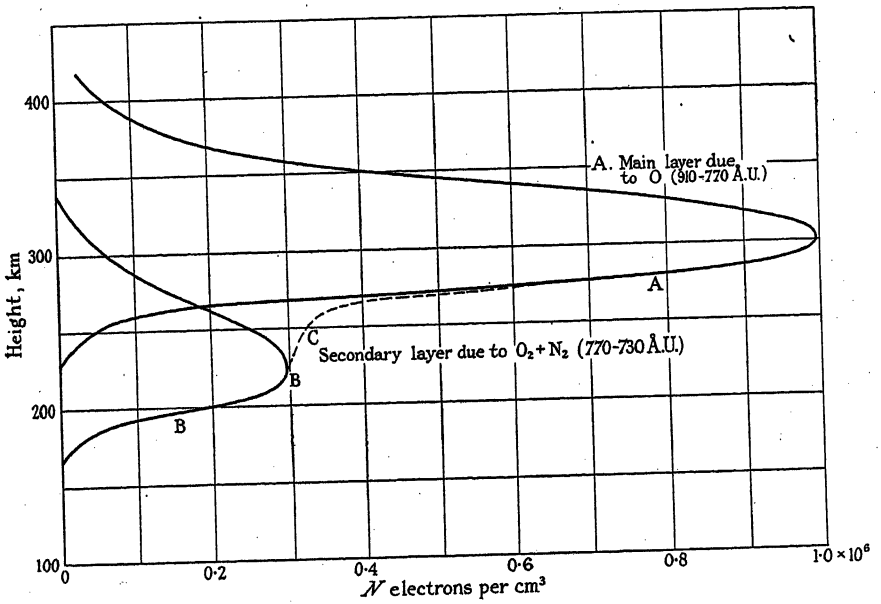


FIG. 9.—Possible ionization of F layer.

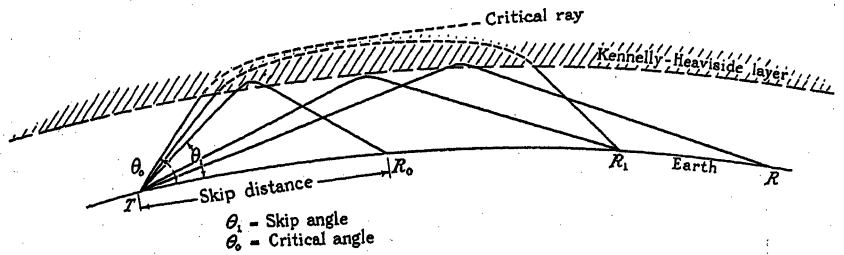


FIG. 10.

in consequence definite electron limitation skip-distances exist, two rays of a definite order exist, i.e. two rays of essentially different paths reach a given point on the earth's surface after one reflection from the Kennelly-Heaviside layer. The general reasoning on which these results are based is not difficult to grasp, and Baker and Rice's mathematical analysis of a particular model gives precision to these ideas.

Thus, consider a transmitter at T and a graded layer (Fig. 10) represented by the shaded portion, and let us follow the trajectories of the rays as the angle of elevation is increased from zero to the critical angle.

With a small angle the target of the ray is at R, say. As we increase the angle the target closes in towards T and comes to a minimum, the skip distance, at R_0, say,

model suggested and investigated by Baker and Rice, in which the refractive index μ is given by

$$\mu^2 = 1 - \frac{\lambda^2}{\lambda_0^2} \sin^2 \tfrac{1}{2}\pi\left(\frac{Z - Z_0}{Z_1 - Z_0}\right) \quad . \quad . \quad (30)$$

or, what is equivalent, a density distribution

$$N = \frac{\pi m}{e^2 \lambda_0^2} \sin^2 \tfrac{1}{2}\pi\left(\frac{Z - Z_0}{Z_1 - Z_0}\right) \quad . \quad . \quad . \quad (31)$$

for the region between $Z = Z_0$ and $Z = Z_0 + 2(Z_1 - Z_0)$, and zero elsewhere.

N rises to a maximum at $Z = Z_1$ and the thickness of the layer is $2(Z_1 - Z_0)$. Z_0 is the height at which the density begins to be appreciable.

In view of our measurements we have taken $Z_1 = 300$ and $Z_0 = 200$ km.

Then the range as a function of θ, the angle of elevation, can be written down in the form given by Baker and Rice:—

$$R = \frac{4\pi r_0(\beta - \theta)}{360} + \frac{4}{\pi}(Z_1 - Z_0)\frac{\lambda_0}{\lambda}\cos\beta K(\sin\alpha) \quad . \quad (32)$$

where β (an auxiliary angle) and θ are in degrees, and λ is the wavelength transmitted.

Our definition of $\sin\alpha$ differs from that of Baker and Rice by the inclusion of the constant C, nearly unity, introduced to make the definition of the minimum wavelength agree with the correct value in the spherical case.

$$C = \left[1 - \gamma\left(\frac{\lambda_0^2}{\lambda^2} - 1\right)\right]^{-\frac{1}{2}} \quad . \quad . \quad . \quad (35)$$

and

$$\gamma = \frac{(Z_1 - Z_0)(2R_0 + Z_1 + Z_0)}{(R_0 + Z_0)^2} \quad . \quad . \quad (36)$$

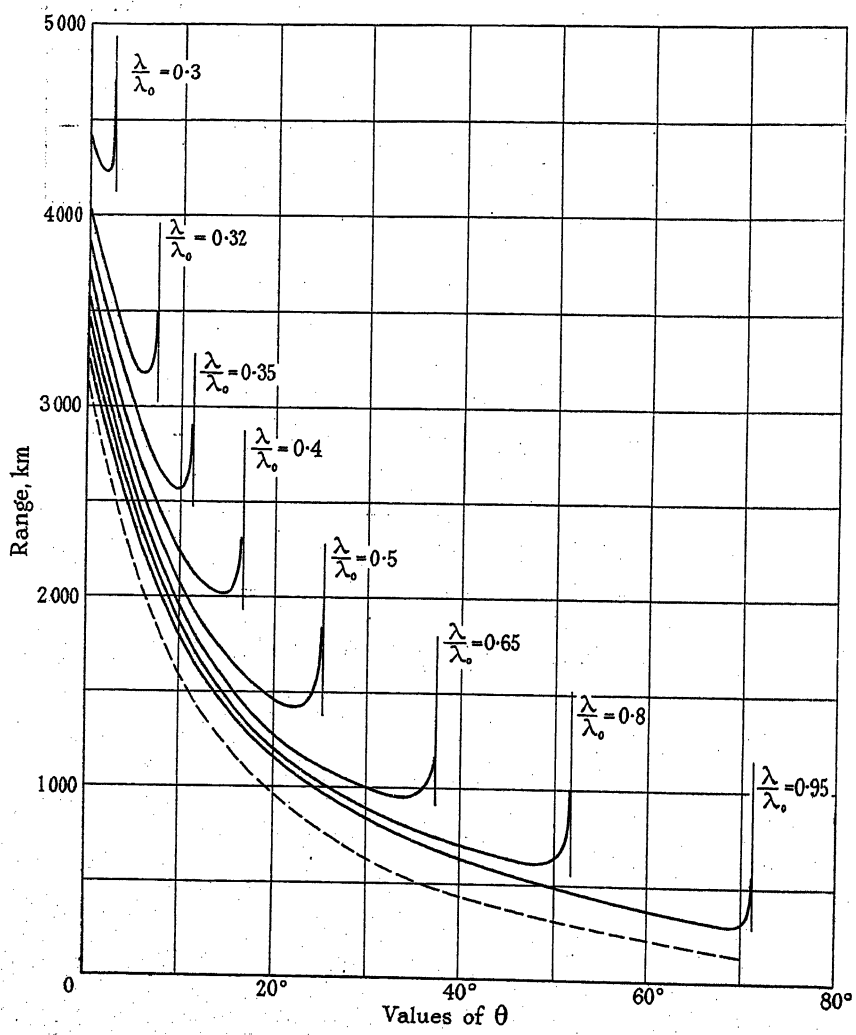


FIG. 11.—Range (R, θ) curves.
$Z_1 = 300$ km.
$Z_0 = 200$ km.

λ_0 is the critical wavelength corresponding to the maximum density N_1 in the F layer. R_0 is the radius of the earth, and β is connected with the angle of elevation by the relation

$$(R_0 + Z_0)\cos\beta = R_0\cos\theta \quad . \quad . \quad . \quad (33)$$

K (sin α) is the complete elliptic function of the first type of the argument sin α, where

$$\sin\alpha = C\frac{\lambda_0}{\lambda}\sin\beta \quad . \quad . \quad . \quad . \quad (34)$$

From this relation curves connecting the range R and θ (the angle of elevation) can be computed for given values of λ/λ_0. They are shown in Fig. 11.

Take, for instance, the one for $\lambda/\lambda_0 = 0{\cdot}65$. It corresponds approximately to the case of transmission on a 20-m wavelength for midday.

As θ increases, the range decreases to a minimum (the skip distance), and then increases very rapidly again near $\theta = \theta_0$ (the critical angle). At a given range, say 1 200 km, there are two values of θ which are appro-

priate to rays which both arrive at R. These angles are 22° and 37·3°. A little consideration of these curves shows that unless the actual distance of transmission is practically an exact multiple of the skip distance, the higher-angle ray of the two is projected at an angle practically equal to the critical angle. On the records, then, the second ray should show itself as another echo at a delay time corresponding to the critical angle, and should not appreciably alter the echo spacings, except when, as indicated above, the distance is a nearly exact multiple of the skip distance. In such cases each echo is likely to be split. Some of the more complicated echo patterns may possibly be due to this cause. On examining the records for the effect no *certain* evidence of it was obtained. A point to be noted is that the higher-angle echo is likely to be very weak, for the following reason. A measure of the energy density in a given ray is, as explained by Baker and Rice, proportional to $d\theta/dR$. Thus the energy emitted through an angular cone lying between θ and $\theta + \delta\theta$ (see Fig. 13) is spread over an annular ring on the earth's surface of radii R and $R + (dR/d\theta)d\theta$. The area of the ring is $2\pi R(dR/d\theta)d\theta$, so that if I is the intensity radiated through the annular cone at the transmitter

$$I \cos\theta d\theta = I' 2\pi R_0 \frac{dR}{d\theta} d\theta$$

and

$$I' \propto \frac{I \cos\theta}{R_0 dR/d\theta} \quad . \quad . \quad . \quad . \quad . \quad (37)$$

The energy density of the ray is proportional to

$$1 \Big/ \left(R \frac{dR}{d\theta}\right)$$

A glance at the curves in Fig. 11 shows that in general, where θ is close to the critical angle, as it is for the secondary ray in all but exceptional cases, $dR/d\theta$ is very large and the energy density in the ray (apart from attenuation) approaches zero. The physical meaning of this is obvious. All the energy radiated in a small angular cone near the critical angle is spread more or less uniformly over the earth in regions beyond R_0, and so the corresponding energy is spread very thinly and the intensity is very small.

The geometrical ray picture ought to be amended by the inclusion of the secondary high-angle rays, as shown in Fig. 10, but these are so weak, in all but exceptional cases, that analysis of the facsimile records is not materially altered.

A number of records taken on Dorchester (37 m, within the skip distance) to show the effect of scattering will be discussed separately, as well as the scattering records on the 60-m Writtle–Somerton records.

PART (2). SIGNAL MEASUREMENT.

Perhaps the main branch of wireless research is signal measurement and the interpretation of the results obtained. After all, the radio engineer is chiefly concerned with producing an adequate signal energy at his receiver. The signal must be not only adequate in intensity but also of correct formation. The radio engineer is not primarily concerned with what happens *en route*, but he finds himself forced to consider the processes of transmission, if only to provide a suitable means of correlating and interpreting the mass of undigested observations accumulated in the last few years of traffic-handling on various beam routes, in research laboratories, etc. It cannot be too strongly urged that the only satisfactory way of doing this is to study the phenomena of radio transmission from a purely scientific point of view. It is only by this means that a reasonable working hypothesis can be obtained by means of which the mass of results can be put in a usable form. The author speaks for himself when he says that the lack of a proper theory often leads one to fail even to *observe* significant facts. It is very often only when, so to speak, the mental eye is opened by theoretical expectation that such facts are even mentally recorded as significant.

The author has noticed cases where no real use of a large mass of observations of this sort has been made, owing to a lack of proper scientific analysis dependent, as it should be, on suitable scientific hypothesis. Wireless owes its origin to the pure theorizing of Maxwell, even though its development was carried out by practical engineers.

The subject of signal measurement has been relegated to the second place in this paper chiefly because a knowledge of the pulse experiments of Breit and Tuve, interference experiments of Appleton, and facsimile results, are absolutely essential for a proper understanding of signal-intensity measurements.

Here again we have a case in which experiments, carried out chiefly with the aim of discovering something about the physics of the upper atmosphere and without any immediate practical application, have yielded results of the utmost significance in the practical branch of communication known as "facsimile transmission," as well as in ordinary telegraphic and telephonic communication.

The material to be discussed consists of a continuous series of measurements made during the year October 1930 to October 1931 on a number of short-wave commercial stations. The measurements were made at Broomfield, near Chelmsford, with a signal-measuring set already described in the *Marconi Review* (No. 30, May and June, 1931). The first three months' results have already been discussed in another issue of the same *Review*. The whole of the material will be considered here and a more comprehensive study of the conditions will be possible.

No very great accuracy is claimed for the measurements. In the first place the signal intensity may vary over a range of 10 to 1 or more during the few minutes required for measurement, and the choice of a representative figure for the field intensity is to a certain extent arbitrary. We find that in general during a short period of 2 or 3 minutes the signal intensity rises to a number of well-defined peaks, of more or less the same intensity, and this peak intensity is taken as the representative figure for the period.

The accuracy in determining a representative value in this manner can be settled by taking the results of two observers measuring, simultaneously with similar sets, a given distant station. A typical example of such a test is shown in Fig. 12. These observations were taken on two different sets in the same building (care being

taken to ensure that there was no interaction). The observations were not taken quite simultaneously, but in all cases except in the period 1700 to 1820 G.M.T., when the signals were very variable, the difference between the two measurements was less than 2 decibels, and the probable error of one with respect to the other as a standard was less than 1 decibel. This is more remarkable for the fact the two sets used different types of attenuators. The question of the absolute accuracy is more difficult to settle. A recent comparison with a Post Office measurement set built on the same lines as that described by Friis,* and using an entirely different method, and a vertical aerial instead of a frame, shows good agreement at 21 m, a difference of about 7 decibels at 16 m, and a difference of — 5 decibels at 34·5 m. The difference appears to decrease to a small value as the wavelength is increased.

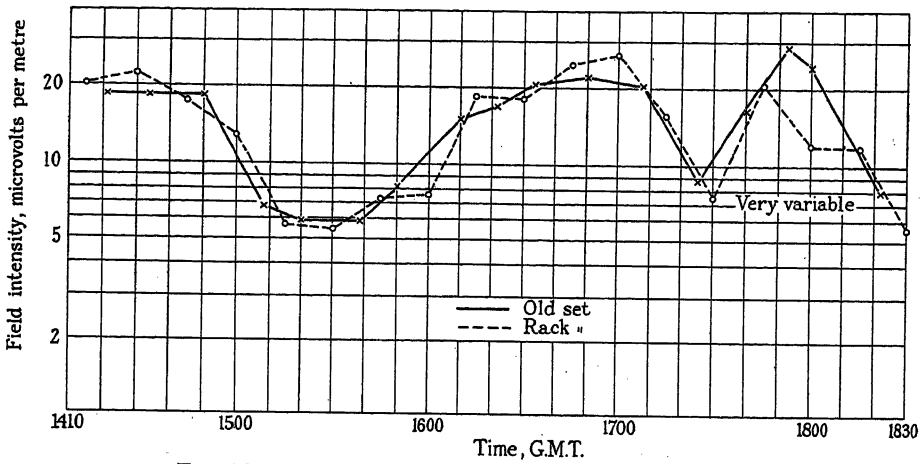


FIG. 12.—New York (WND), 16·4 m, 26th August, 1931.

The cause of these differences has not yet been discovered, but they may possibly be due to the fact that the two instruments are not measuring the same quantity. That employed by the author measures the magnetic field at about 1·5 m above the earth's surface, while the Post Office instrument with a vertical aerial measures the electric field at a mean height of about 4 to 5 m above the earth's surface. These two quantities are not necessarily the same. The results therefore suffer from some uncertainty in absolute value, but not enough to affect the main conclusions.

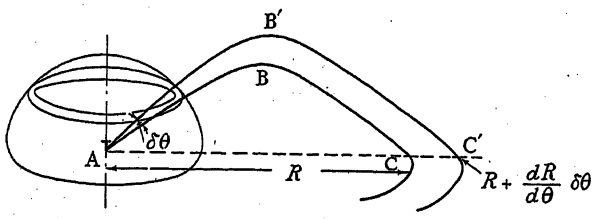


FIG. 13.—Focusing factor.

The stations measured were as far as possible those with well-defined continuous-wave carriers, i.e. regularly working telephone stations and multiplex beam stations. Such stations are more easily measured with the author's apparatus, in which the heterodyne note of the signal has to be matched by the heterodyne note of the auxiliary signal generator. With modulated transmissions the heterodyne note of the signal is complex and more difficult to match.

For completeness, however, the Marconi beam stations in India and Australia were included, although they transmit modulated continuous waves.

A list of the stations observed is given in Table 6.

TABLE 6.

Station	Approximate wavelength	Nature of transmission
	m	
Java (Bandoeng)	14·5	Telephone
Buenos Ayres ..	15·2	Telephone
Java (Bandoeng)	16	Telephone
Cape Town ..	16·08	Multiplex telegraph
Poona	16·85	Modulated continuous wave
New York	16·4 / 20·7	Telephone
Melbourne ..	25·7	Modulated continuous wave
Rugby ..	27·8	Telephone
Sydney ..	28·6	Telephone
Montreal ..	32·1	Multiplex telegraph
Bodmin (GBK)	32·3	Multiplex telegraph
New York ..	32·5	Telephone
Cape Town ..	33·7	Multiplex telegraph (changed to modulated continuous wave)
Bodmin (GBJ)..	34	Multiplex telegraph (changed to modulated continuous wave)
Grimsby ..	34·2	Modulated continuous wave
Poona ..	34·5	Modulated continuous wave
New York* ..	44·41	Telephone
Rugby* ..	43·45	Telephone
Cairo† ..	21·7	Modulated continuous wave

* Added in November. † Added in February.

* H. T. FRIIS and E. BRUCE: *Proceedings of the Institute of Radio Engineers*, 1926, vol. 14, p. 507.

There were only two operators, so that it was not possible to keep a 24-hour watch.

In general two 8-hour watches were kept from 0800 to 2400 G.M.T. for the first three weeks in the month, and a night watch for the remaining week. This was

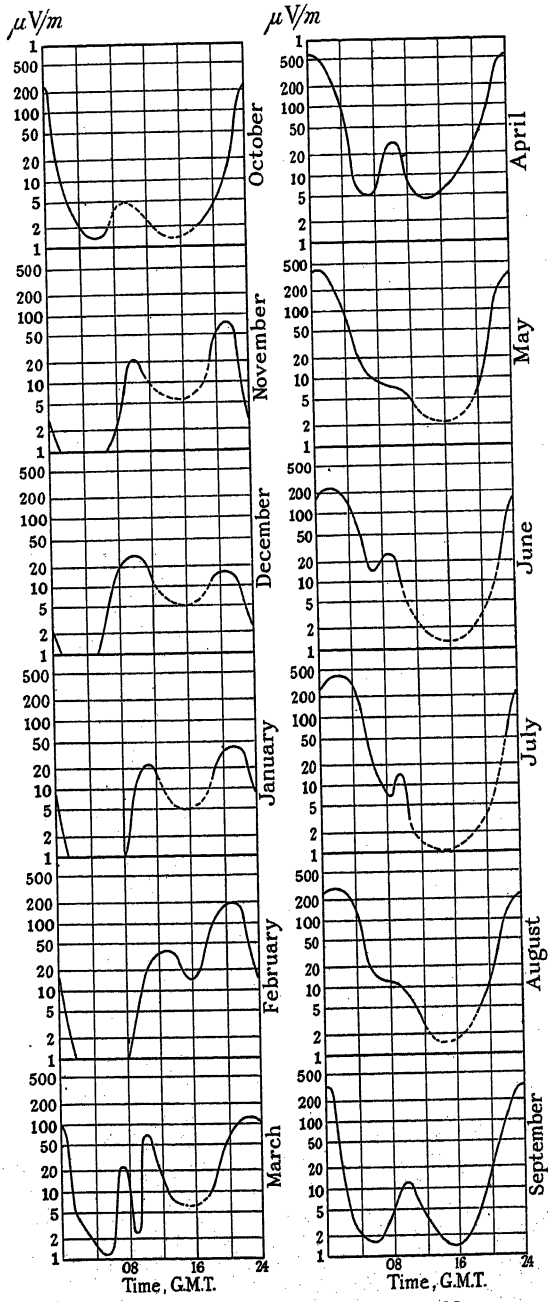


FIG. 14.—Montreal, 32 m, 1930–31.

appropriate to winter conditions when all but the longest waves disappeared at night. Later (about February) alternate weeks were devoted to day and night watches. In this manner representative monthly values for all hours of the day and night could be obtained. The number of readings obtained per month on a given station depended to a certain amount on the nature of the working of the station, but in most cases it was of the order of 100 to 200, quite sufficient to show a well-defined diurnal curve (during the hours at which the station worked).

In general, monthly means were taken for 2-hourly

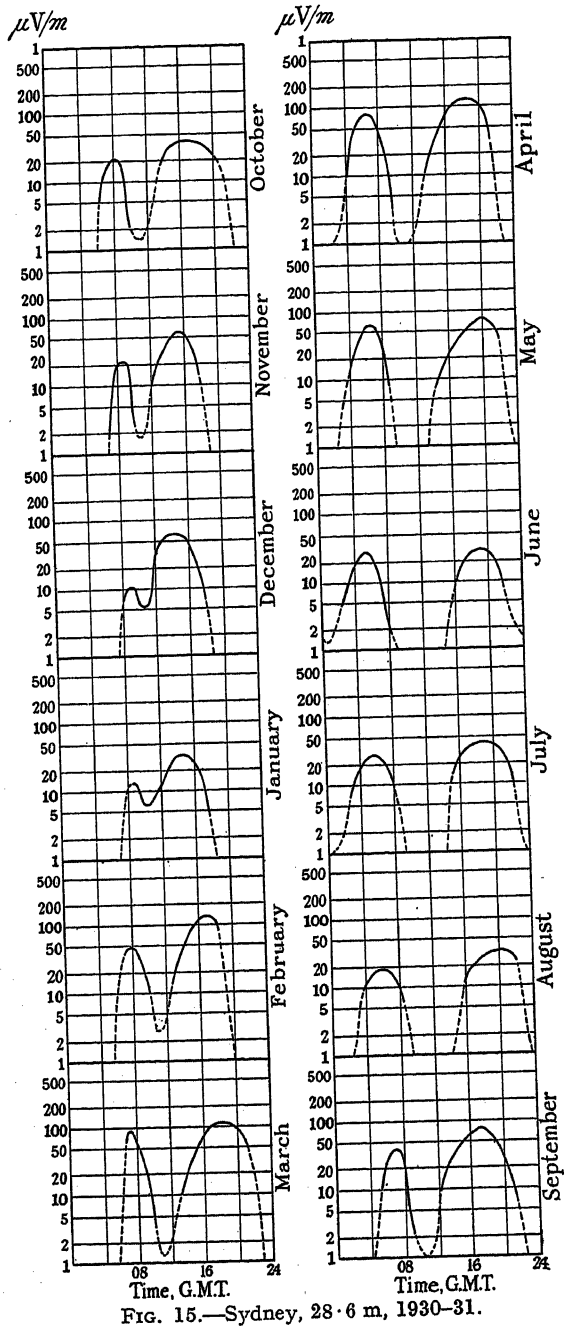


FIG. 15.—Sydney, 28·6 m, 1930–31.

periods, except where the variation was too rapid. This may be of questionable value in some cases where the scatter of the points is very large, as in the example shown in Fig. 16B, which gives the measured values of Montreal (32 m) during August.

The extreme values at a given time may vary from fractions of a microvolt to 80 or 100 μV. For the pur-

poses of analysis, however, some definite figure must be given, and the average, being the simplest representative figure, was taken. In many cases it was possible to reject some of the readings as abnormally low on account of disturbed conditions.

The averages are intended to give as far as possible the normal transmission characteristic. In any future statistical investigation in which the effects of magnetic disturbance or other cosmic conditions is sought, it will be necessary to deal with all the individual values. The value of the present material would be enhanced if the complete material were published in some form, but it

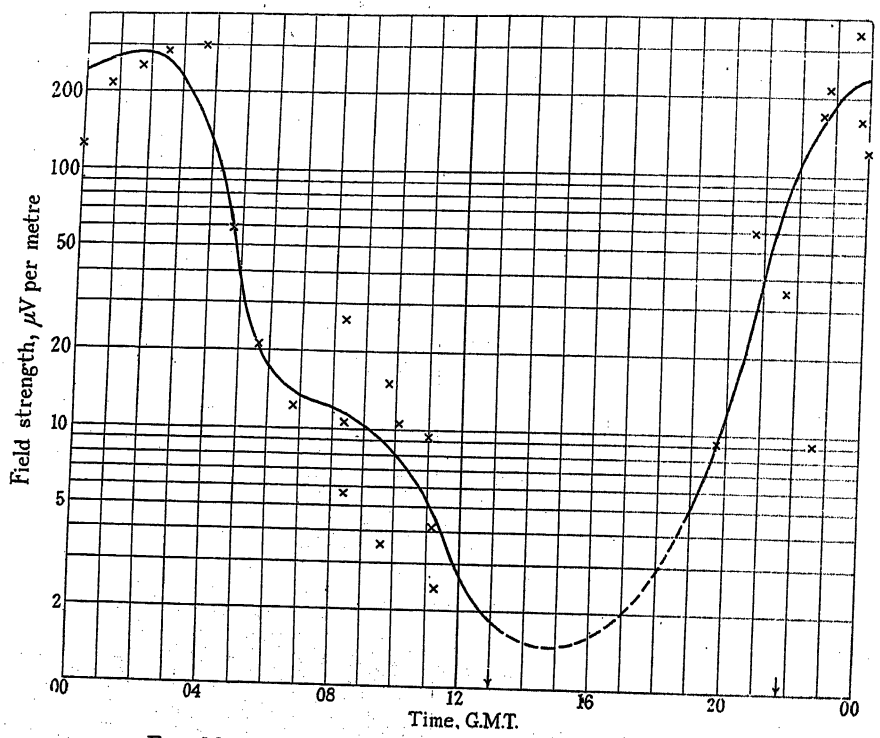


FIG. 16A.—Montreal, 32 m, August 1931, normal days.

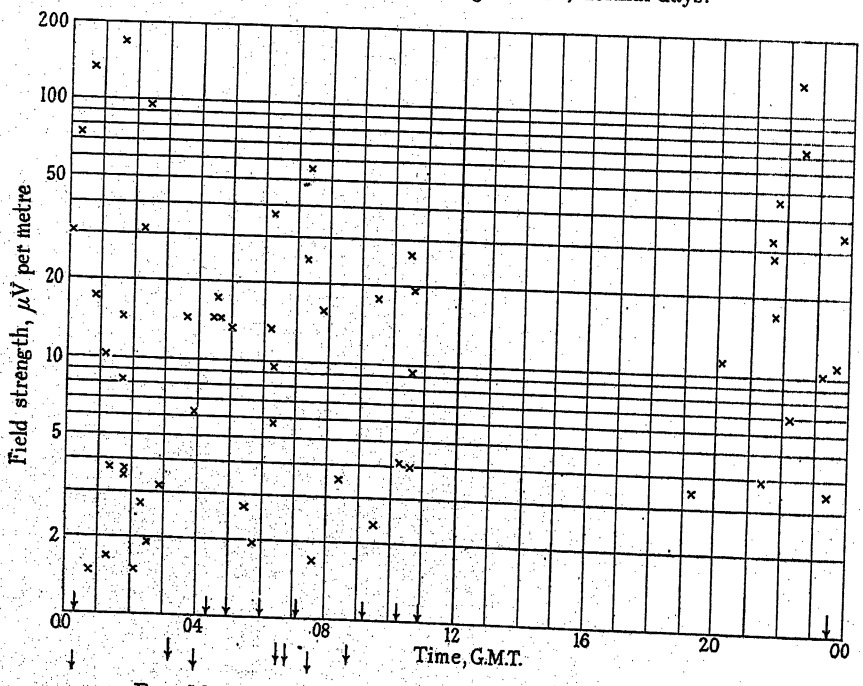


FIG. 16B.—Montreal, 32 m, August 1931, abnormal days.

is unreasonable to encumber a general paper of this kind with a large mass of results, so that it would appear best to publish the whole material separately and limit ourselves to a general discussion and analysis of the results here.

Some examples of the seasonal changes in the monthly mean diurnal curves are illustrated in Figs. 14 and 15. The curves illustrate the results obtained on Montreal (32 m) and on Sydney (28·6 m).

From these examples it will be realized how difficult it is to obtain definite average values for monthly means, etc., free from any arbitrary element. Nevertheless, in any comparison with theory we have to give a definite field strength for any particular time of the day and route; for the theory, at least at present, cannot take account of the accidental and incalculable variations in the state of the Heaviside layer which produce such a profound effect in transmission.

In any attempt at explanation we are forced, however, to consider the possible mechanism by which these effects are caused, in order to define a "normal" observation and reject abnormal ones. One method is to take the mean of all observations, reject all that diverge more than a certain percentage from the mean, and proceed to another mean; but this method is very arbitrary. A hint as to the cause of this variability is contained in the fact that a cursory examination of the material shows that the routes which pass closer to the magnetic poles are most subject to variation.

We have the suggestion, therefore, that in the main the excessive variability is caused by magnetic disturbances. A day-to-day variability in the E-layer density is known to occur, and the established correlation between short-wave radio and magnetic conditions (on a large scale) suggests that the correct procedure is to eliminate those observations taken on days which are disturbed magnetically. Normal days will then be magnetically quiet ones. The soundness of this procedure will be confirmed if the resultant "normal" values are considerably less variable than the whole material.

The examples shown in Figs. 16A and 16B for normal and abnormal days seem to the author to be fairly convincing, and we can conclude that a large part of the variability is due to magnetic disturbance. In the analysis, only normal days, as far as is possible, will be considered. We have, then, a year's series of observations which can be used to test any reasonable hypothesis as to the mode of transmission of short wireless waves.

In formulating a theory we are guided almost wholly by the information afforded by the facsimile records and allied results, which have given us, as we have seen, a clear idea of the normal mode of propagation and a representative model of the Heaviside layer.

This mode of transmission is a zigzag reflection of the rays between the earth and the Heaviside layer. In the case of the shorter waves, with which we are dealing here, the ray has to pass through the E layer twice in going up to the F layer and back.

From our knowledge of the density of the E layer we know that the ray is not appreciably deflected (except for longer waves at glancing incidences).

The collision frequency of electrons and molecules in the lower-lying layer between 5×10^6 and, say, 10^5 is relatively appreciable (compared with the frequency of the waves, 10^7) and α $[= \nu_c/(\pi\nu)]$, though small, is appreciable, and attenuation ensues. A representative distribution of N_e in the E layer being known, as well as the ray path, it should be possible to calculate the attenuation of each ray.

In estimating the intensity, E, produced by any ray, there are two effects to be taken account of. One is the attenuation—already discussed—and the second is what, for want of a better word, the author calls the "focusing" effect. This can best be explained by reference to Fig. 13.

Thus let ABC and AB'C' be any two adjacent rays. The energy sent out in the cone between AB and AB' is distributed on the earth in the annular ring enclosed by two circles of radii AC and AC' respectively. It is clear that the smaller the annular ring the greater the energy density and hence the field intensity.

In the case where the rays are focused at C the energy density is infinite. In other cases it may be very small, e.g. the case discussed on page 425.

By equating the energy transmitted through the cone to that through the annular ring we arrive at the expression

$$E^2 \propto \frac{I \cos\theta}{R \,.\, dR/d\theta} \quad . \quad . \quad . \quad . \quad . \quad (38)$$

This expression for R, the range as a function of θ, can be obtained if the distribution of N in the upper layer is known.

Baker and Rice and H. Lassen have made calculations on various reasonable assumptions as regards the distribution of N. These give rise to two values, one for the short-range rays and the other for the long-range rays. For the former the calculated values do not differ appreciably from the inverse-distance law (except possibly in the neighbourhood of the skip distance). Thus the ratio of $E_{10\,000}/E_{5\,000}$ in the published curve given by Lassen is $\frac{1}{2\cdot3}$ instead of $\frac{1}{2}$ for the inverse-distance law.

In general the distant ray is negligible, and the author has found no definite evidence of its existence in the facsimile records. The fact that the effective height does not vary largely with the angle of elevation is additional experimental proof of the inverse-distance law for each separate ray. For if this is the case the equivalent rays behave as if they were reflected at a definite (fictitious) surface, and in such a case it is easy to see that the energy distribution at C, say, is exactly that which would have been produced by a vertical image at T_1, say (see Fig. 17), and is inversely proportional to TC, i.e. to ρ.

Each ray then contributes a field intensity, apart from attenuation, of an amount

$$\frac{3\pi(\sqrt{W})f(\theta)^*}{R} \quad . \quad . \quad . \quad . \quad . \quad (39)$$

* $f(\theta)$ represents the polar diagram of the energy distribution in the vertical plane; it is $\cos^2\theta$ for the case of a small vertical aerial. For any other case it satisfies the condition that $\frac{3}{2}\int_0^{\pi} \cos\theta f(\theta) d\theta = 1$.

very nearly (assuming the angle is small, and putting R for ρ). The field may either be horizontally or vertically polarized, so that, considering the energy to be equally distributed between the horizontally polarized and vertically polarized waves, we have for the contribution to E (vertical)

$$\frac{3\pi}{\sqrt{2}}\frac{(\sqrt{W})f(\theta)}{R} \text{ (nearly)} \quad . \quad . \quad . \quad . \quad (40)$$

In general we have seen from the facsimile results that there are n rays, and this number n is the nearest integer just less than the ratio of the total range R to d_0, the skip distance.

Since the difference in length of any two of these rays is a very large number of wavelengths, we may consider all the rays to be random-phased, and, instead of taking the resultant field strength as n times that of one, we have, according to Rayleigh's law, to add energies and

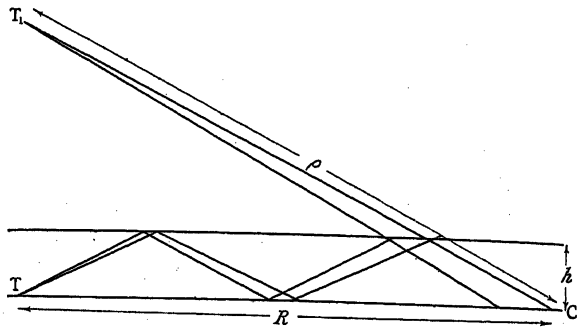


FIG. 17.—Reflection at a virtual layer.

not amplitudes and so multiply (40) by $\sqrt{n}$ in order to get the resultant average intensity

$$E_{res.} = \frac{3\pi\sqrt{n}(\sqrt{W})f(\theta)}{\sqrt{2}.R}$$

to our degree of approximation, but since we can replace n by R/d_0 this becomes

$$E = \frac{3\pi(\sqrt{W})f(\theta)}{\sqrt{(2d_0R)}} \quad . \quad . \quad . \quad . \quad (41)$$

This should be the natural form of the amplitude factor (apart from attenuation) in the transmission formula.

It is to be noticed that it varies as $1/\sqrt{R}$ and not as $1/R$.

The $1/\sqrt{R}$ form is invariably associated with the transmission between layers, whereas the $1/R$ form is not. It can easily be deduced from energy considerations for the waves between layers spread out cylindrically and not spherically. Thus where there is no loss of energy the whole of the energy transmitted, i.e. W, is radiated through the cylindrical ring of radius R and height h. Therefore the average flow of energy is $W/(2\pi Rh)$ and the corresponding field intensity is proportional to the square root of this, i.e. $K\sqrt{W}/\sqrt{(2\pi Rh)}$ and varies inversely as $\sqrt{R}$.

The inverse-distance law is not the expression of transmission without loss, as often assumed, but the inverse $\sqrt{R}$ law is. Any considerable divergence from the form above must inevitably be attributed to attenuation. The fact that, in actual practice, the differences from wavelength to wavelength and time to time are enormously greater than can be accounted for by a formula of the type above, seems to the author to be a complete proof that the major factor in the control of short-wave daylight signals is attenuation.

An example will make this clear. At midday a 20-m beam station at 1 000 km distance would be inaudible in England, but a 16-m signal would have a field intensity of about 15 to 20 decibels above 1 microvolt. A field intensity of -20 decibels is easily heard. The difference in intensity must therefore be greater than 35 to 40 decibels. Estimated from the inverse $\sqrt{R}$ formula given above, the difference

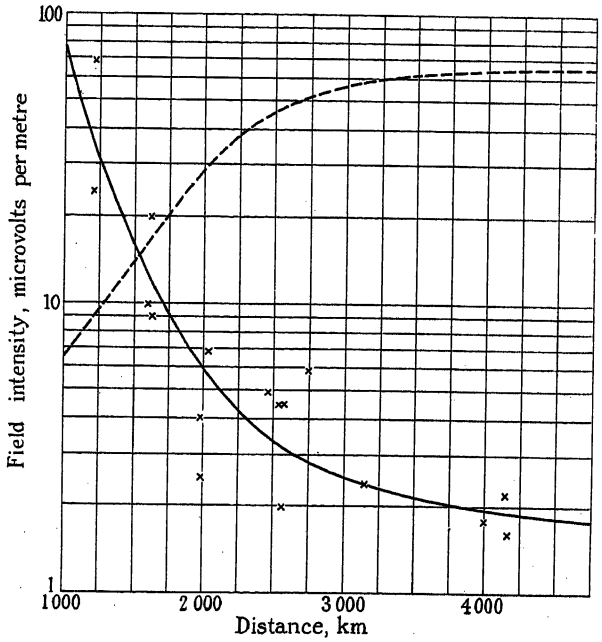


FIG. 18.—Results obtained on S.S. "Homeric," 24·2 m, 4th–11th June, 1930.

cannot be greater than the square root of the ratio of the skip distances of these two waves, i.e. approximately $\sqrt{(1\,300/900)} = 1{\cdot}21$, or 1·6 decibels. Similar examples could be multiplied indefinitely. We can therefore confidently assert that the major controlling factor in short-wave daylight transmission is attenuation.

At night time the effect of attenuation is not so marked, and the main factor is probably electron limitation, although the effect of attenuation must not be neglected.

The next step is to determine—if possible—the attenuation. Where there is any doubt, as there must be, as to the value and form of the "focusing" factor, the only definite method of finding the attenuation curve is actually to determine the field-strength/distance curve of a station. Opportunity for doing this was afforded by the equipment of the S.S. "Homeric" and the S.S. "Empress of Britain" with telephone transmitters working on spot waves in the neighbourhood of 24 m and 75 m. Unfortunately the results are not very numerous: they are, however, sufficient to give a fairly

well-defined attenuation curve. Together with these we have the results published by Anderson.* These

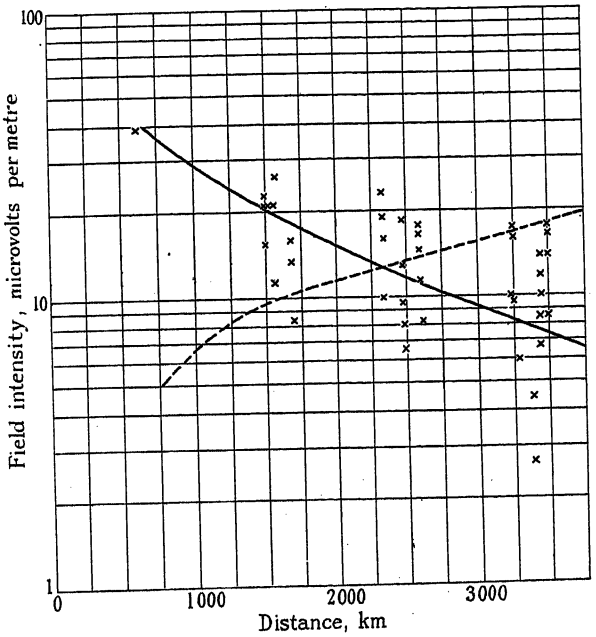


FIG. 19.—Results obtained on S.S. "Homeric," 24·2 m, 6th–9th July, 1931.

give the variation of signal strength with distance of the 75-m transmission from S.S. "Leviathan," measured from October to December, 1929.

with equal justification be said to approach the inverse square-root law, leaving 2 or 3 decibels at 5 400 km distance to be accounted for by attenuation. This is a definite case where the night attenuation is small. In the two attenuation curves obtained on S.S. "Homeric" for a 24·2-m transmission (Figs. 18 and 20) in daytime the divergence between the actual observations and those calculated on the inverse square-root law is very marked, and is also very different in the two curves, the effective attenuation in June 1930 being much greater than that in July 1931. The results, so plotted, represent a complex problem. If we attempt to analyse the results in the usual manner by assuming E to be of the form

$$E = \frac{1}{\sqrt{2}} \cdot \frac{3\pi(\sqrt{W})f(\theta)}{\sqrt{(d_0 R)}} e^{-\alpha R} \quad . \quad . \quad . \quad (42)$$

we find that the signal intensity cannot be put in this form, at least for the "Homeric" results. Taking the logarithm of both sides, we get

$$\log E = \log \frac{3\pi(\sqrt{W})f(\theta)}{\sqrt{(2d_0 R)}} - \alpha R$$

and the quantity

$$\log\left[E \Big/ \frac{3\pi(\sqrt{W})f(\theta)}{\sqrt{(2d_0 R)}}\right] = -\alpha R \quad . \quad . \quad (43)$$

should be linear in R and the curve representing this relation should pass through the origin.

In actual fact this is far from the case, as the curve representing $\log \dfrac{3\pi(\sqrt{W})f(\theta)}{\sqrt{(2d_0 R)}} \Big/ E$ as a function of R clearly indicates.

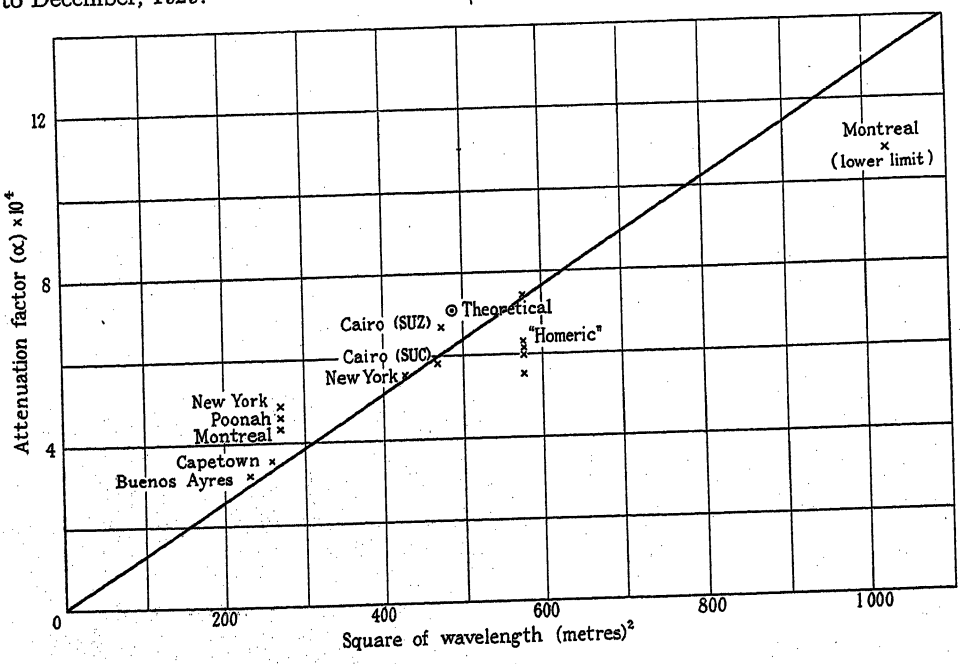


FIG. 20.

The curve shows night values. The upper limit of these approaches the inverse-distance law, or might

No reasonable amount of alteration to the constants in the first factor will make the dotted curve represented in Fig. 19 approximate to a straight line

* *Proceedings of the Institute of Radio Engineers*, 1931, vol. 19, p. 1150.

passing through the origin. This is in spite of the fact that in the range between 1 000 km and 3 500 km the derived curve for the "Homeric" is approximately linear. It is, however, very far from passing through the origin.

The type of attenuation curve such as this in which the attenuation coefficient is large for short distances and decreases with increasing distance is very familiar in all branches of physics, and implies the attenuation of non-homogeneous radiation in the sense that the total radiation is composed of different parts which have different attenuation coefficients. The highly attenuated components are rapidly absorbed, leaving the slightly attenuated components of less amplitude to carry on to relatively great distances. In the case under consideration the attenuation of this type is naturally explained on the hypothesis that the rays of each order are differently attenuated. We have clear evidence of this from the facsimile results in which we found evidence that the high-angle rays are much more attenuated than low-angle rays, especially at a time when the F layer is at its maximum density. We can therefore attribute the "Homeric" results to rapid attenuation of the high-angle rays, leaving the lower-angle rays to carry on with less attenuation. It is unfortunate, perhaps, that results for midday were plotted when the difference between high- and low-angle attenuation is a maximum. This is the time, however, when conditions are stationary. At other times the rapid change of path conditions with time makes it difficult to obtain sufficient material from which to derive a definite value of the attenuation. A few points would be sufficient were it not for the variability of results which makes it imperative to obtain a large number of points and take the average.

These considerations lead to the following expression for the resultant intensity. We have seen that each ray contributes a field

$$3\pi(\sqrt{W})f(\theta_n)/\sqrt{2}R$$

where $Wf^2(\theta_n)$ is the power radiated in the direction θ_n and R the distance between transmitter and receiver. This is apart from attenuation, which we have seen must play an important part in short-wave day transmission.

Thus E_n can be expressed

$$E_n = \frac{3\pi}{\sqrt{2}.R}(\sqrt{W})f(\theta_n)e^{-\alpha_n R} \quad . \quad . \quad (44)$$

introducing by the exponential the effect of attenuation, and the total resultant E will be the square root of the sum of the squares of the components, i.e.

$$E_{res.} = \frac{3\pi}{\sqrt{2}.R}\left\{\Sigma(W_n)f^2(\theta_n)e^{-2\alpha_n R}\right\}^{\frac{1}{2}} \quad . \quad (45)$$

It might be thought possible to analyse the actual attenuation curve into an expression of this sort, especially as we know from facsimile experiments the number of components, i.e. rays, into which the curve has to be analysed. In the author's opinion, however, the curve is not accurate enough for this purpose.

This, then, is the general expression for E.

In the case of the shorter waves all the rays are radiated at shallow angles, and we may take $f(\theta_n) = 1$, thus assuming that the energy radiated along each ray is approximately the same.

In this case we have

$$E_{res.} = \frac{3\pi\sqrt{W}}{\sqrt{2}.R}\left\{e^{-2\alpha_0 R} + e^{-2\alpha_1 R} + \ldots + e^{-2\alpha_n R}\right\}^{\frac{1}{2}} \quad (46)$$

Let us suppose that α_0 is the least of the attenuation coefficients; then when R is great enough all the terms $e^{-2\alpha_n R}$ are negligible compared with $e^{-2\alpha_0 R}$, and $E_{res.}$ is expressible in the form

$$\frac{3\pi\sqrt{W}}{\sqrt{2}.R}e^{-\alpha_0 R} \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

At the other extreme where the transmission distance is small or the difference in the α's small, we can define a mean attenuation $e^{-\bar{\alpha}R}$ such that

$$ne^{-2\bar{\alpha}R} = \Sigma e^{-2\alpha_n R} \quad . \quad . \quad . \quad . \quad (48)$$

where n is the number of rays and E becomes

$$E_{res.} = \frac{\sqrt{n}\,.\,3\pi\sqrt{W}}{\sqrt{2}.R}e^{-\bar{\alpha}R} \quad \text{or} \quad \frac{3\pi\sqrt{W}}{\sqrt{(2d_0 R)}}e^{-\bar{\alpha}R} \,. \quad (49)$$

In such a case $\bar{\alpha}$ is not a constant independent of R unless all the α's are equal, in which case it is equal to any of them. Where the α's are nearly equal and R not too great $\bar{\alpha}$ is nearly constant, and this is a convenient formula. In any actual case $E_{res.}$ should lie between these extremes. It should be noted that $\bar{\alpha}$ is always greater than α_0, so that

$$\frac{3\pi\sqrt{W}}{\sqrt{(2d_0 R)}}e^{-\alpha_0 R} > E_{res.} > \frac{3\pi\sqrt{W}}{\sqrt{2}.R}e^{-\alpha_0 R} \quad . \quad (50)$$

If α_0 were known, we should have a means of testing this inequality, or if we consider α_0 unknown this inequality may be considered to be a relation for determining the extreme limits for α_0, i.e. $\bar{\alpha}_0$ and $\underline{\alpha}_0$ given by

$$\frac{3\pi\sqrt{W}}{\sqrt{(2d_0 R)}}e^{-\bar{\alpha}_0 R} = E_{res.} = \frac{3\pi\sqrt{W}}{\sqrt{2}.R}e^{-\underline{\alpha}_0 R} \quad . \quad (51)$$

For transmission over great enough distances α_0 may be determined very approximately from the relation

$$E_{res.} = \frac{3\pi\sqrt{W_0}}{\sqrt{2}.R}e^{-\alpha_0 R} \,. \quad . \quad . \quad . \quad (52)$$

all the quantities except α_0 being known. In a number of the measured transmissions these conditions appear to be satisfied.

If we take the "Homeric" results as representative, then after a distance of some 2 000 or 3 000 km the attenuation appears to have attained its constant value α_0. Again, in the facsimile on South Africa at or near midday, all the rays but one appear to have been weeded out, which implies that the above condition is satisfied.

For the purposes of analysis the conditions should be as uniform as possible along the path. This is achieved, to a great extent, by considering those paths for which the mean altitude of the sun along the path is a maximum and for which the path is wholly in daylight. Conditions

are in general stationary at such a time and well-determined values of a can be obtained.

In Table 7 most of the possible examples obtained during the year's interception which satisfy these conditions are made to yield values of the limits of α_0.

Seasonal variations are eliminated as far as possible by choosing that material for which the mean conditions of ionization, as far as can be judged, are constant along the path.

In the nomenclature of a previous paper* the paths were chosen to lie entirely in the A grade (this being the sunlit grade of maximum ionic density).

TABLE 7.

Station	Wavelength	$\alpha_0 R$ (R = 10 000 km)	
		Upper limit	Lower limit
	m		
Buenos Ayres	15·2	4·11	3·40
South Africa	16·01	4·61	3·57
Poona, India	16·4	5·00	4·60
New York Telephone	16·0	5·96	4·90
Montreal	16·5	6·34	4·35
New York Telephone	20·7	5·88	5·56
Cairo (SUC)	21·7	8·81	5·85
(SUZ)		9·80	6·70
"Homeric"	24·2	—	6·01 (4·85, 6·2, 7·5, 5·52)
Montreal	32	—	14·0 10·8 (lower limit)

If we consider the lower limit to be nearer to the true value of α_0, then we find that α_0 increases rapidly with the wavelength. We find, in fact, that α_0 is very nearly proportional to λ^2. In Fig. 20, α_0 is plotted with λ^2 as abscissæ. The relation is nearly linear.

Ultimate Range.

Comparing stations of the same power in the A grade and at long ranges, E can be expressed in the form

$$E = \frac{3\pi\sqrt{W}}{\sqrt{2}\,.\,R} e^{-\beta_0\lambda^2 R} \quad . \quad . \quad . \quad . \quad (53)$$

Then except for the first factor, involving $1/R$, which only varies relatively slowly compared with the exponential, the signal-level will be the same if $\beta_0\lambda^2 R$ is the same for all the stations, i.e.

$$\beta_0\lambda^2 R = \text{constant} \quad . \quad . \quad . \quad . \quad (54)$$

The range R, then, at which the signals reach a certain level, will be inversely proportional to λ^2.

In a previous examination of a very large amount of material in and before 1928, in which signal strengths were estimated on the R scale, it was found that the range was indeed very closely inversely proportional to λ^2. Some of the evidence has been published in previous papers.

This analysis refers to daylight transmission, i.e. A and B grades. It is not necessarily true of night transmission, which appears to be only slightly attenuated.

The expression

$$E = \frac{3\pi\sqrt{W}}{\sqrt{2}\,.\,R} e^{-\beta_0\lambda^2 R}$$

really refers to a flat earth.

The correction for a spherical earth can easily be made. If ϕ is the angle subtended by the range R at the earth's centre, and if R_0 is the earth's radius, so that $R = R_0\phi$, then we have to replace R^2 by $R_0^2\phi \sin\phi$. When ϕ is small it is obvious that the difference is also very small, because we can replace $\sin\phi$ by ϕ and obtain

$$R_0^2\phi^2 = R^2 \quad . \quad . \quad . \quad . \quad . \quad (55)$$

In the other limiting formula, where the whole n rays are equally attenuated,

$$E = \frac{3\pi\sqrt{W}}{\sqrt{(2d_0R_0\sin\phi)}} e^{-\beta_0\lambda^2 R} \quad . \quad . \quad . \quad (56)$$

Even though α_0 tends to zero as the wavelength decreases, and appears to reduce the attenuation to small values, the signal obtained is well below the true value for lossless transmission.

This is clear when we compare the formula for lossless transmission, i.e. approximately $\frac{3\pi\sqrt{W}}{\sqrt{(2d_0R_0\sin\phi)}}$, with the limiting form $\frac{3\pi\sqrt{W}}{R_0\sqrt{(2\phi\sin\phi)}}$, the ratio being $\sqrt{[d_0/(R_0\phi)]}$ or $\sqrt{(d_0/R)}$ which may be of the order of $\frac{1}{5}$ or $\frac{1}{6}$ for long-distance transmission.

To put the matter concisely, though perhaps not too accurately, short waves enable us to attain enormous ranges but only with relatively small signal intensity. It is only a small fraction of the radiated energy that is able to stay the course. We have here the explanation of the fact, so often observed, that although the shorter waves of the short wave-band are necessary to cover long ranges, the signal intensity obtained is often disappointingly small. A cursory examination of the signal-intensity records shows that high signal-levels are always attained with longer waves.

These conclusions have been obtained purely on experimental evidence of facsimile, attenuation curves, and measured signal intensities. No hypothesis concerning the mechanism of the Heaviside layer has been used, except what has been tested by experiment. When we seek answers to the question naturally suggested by these results, we have to employ some more or less definite theory of the Heaviside layer. One such question is: Which are the more highly attenuated rays and which are those that carry on for a long distance? The evidence from facsimile results supplies an immediate answer to this question.

The absence of high-angle rays on South Africa (16 m) at midday and on South Africa (32 m) in the early evening, the absence of multiple echoes on round-the-world signals, and many similar observations already

* "World-Wide Communications," paper read at the World Engineering Congress, Tokyo.

quoted, show that high-angle rays are more attenuated than low-angle rays. Whether this is always the case cannot be definitely stated, although theoretical reasons lead the author to suspect that it is practically always so. The question why it should be so can only be answered by reference to our simplified model of the Heaviside layer. Facsimile results show us that normal transmission is effected by a sheaf of rays which zigzag between the earth and the Heaviside layer. An nth order ray will make $2n$ passages through the lower E layer. As we have seen, the attenuation in this layer on account of electron collision with molecules is appreciable, even on the shorter waves. If we know the ray path and the distribution of ionic density and collision frequency in the E layer we have the data for calculating the attenuation of any ray in its passage through this layer.

The data given on page 423 supply us with a representative value for the E grade.

The conception of the "optical thickness" of the E layer is helpful here. This is the quantity

$$\tfrac{1}{2}\int\left[\alpha_z\left(\frac{\nu_0^2}{\nu^2}\right)_z dz\Big/\sqrt{\left(1-\frac{\nu_c^2}{\nu^2}\right)}\right] \quad . \quad . \quad (57)$$

where z is the height, α_z the ratio $\nu_c/(\pi\nu)$, ν_c the collision frequency, and ν the actual frequency. ν_c is a function of z, ν_0 is the critical frequency corresponding to any height z in the layer. ν_0^2/ν^2 is another numerical ratio. The integral is therefore of the dimension of a length, i.e. the optical thickness T of the layer.

If we multiply by $2\pi/\lambda$ and take the exponential, $e^{-\frac{2\pi}{\lambda}T}$, we get the attenuation of a ray passing once vertically through the layer.

If the ray passes through the layer obliquely at an angle of elevation θ, then the length of passage is increased in the ratio of $1/(\sin\theta)$ to 1, so that the total attenuation in this case is

$$e^{-\frac{2\pi}{\lambda}\cdot\frac{T}{\sin\theta}} \quad . \quad . \quad . \quad . \quad . \quad (58)$$

An nth-order ray makes $2n$ passages through the layer. Therefore the attenuation of an nth-order ray is

$$e^{-2n\frac{2\pi}{\lambda}\cdot\frac{T}{\sin\theta}} \quad . \quad . \quad . \quad . \quad . \quad (59)$$

Where the earth's curvature can be neglected, $h/R_1 = \tan\theta$, where $R_1 = R/(2n)$ and R is the total range, i.e. $2n = R/R_1 = (R\tan\theta)/h$, and substituting for $2n$ the total attenuation of an nth order ray is

$$e^{-\frac{R\tan\theta_n}{h}\cdot\frac{2\pi}{\lambda}\cdot\frac{T}{\sin\theta_n}} = e^{-\frac{R}{h\cos\theta_n}\cdot\frac{2\pi T}{\lambda}} \quad . \quad (60)$$

where θ_n is the angle of elevation of the nth-order ray. Where the rays are all confined to a sheaf for which the maximum angle is so small that the difference between $\cos\theta_n$ and 1 can be neglected, *each ray is attenuated the same amount.* With a low-order ray the smaller number of passages through the E layer is practically compensated by the greater length of each passage. Where the maximum ray angle is less than 25° and the total attenuation is of the order $e^{-3\cdot6}$ there is only a difference of 3·2 decibels between the highest- and lowest-angle ray over a distance of about 10 000 km (on 16-m wave). This certainly does not account for the high-angle attenuation observed.

We can calculate the value of T, the optical thickness of the lower layer, when the density distribution and collision frequency distribution are known.

From the results tabulated on page 422, Fig. 21, representing the value of $\frac{1}{2}\alpha_z\nu_0^2/\nu^2$ as a function of the height, has been constructed.

At heights above the region where N is a maximum the value of N is unknown, but at such heights, so long as we assume $N < N_{max.}$, as we must, the collision frequency is so small that there is hardly any appreciable contribution to the integral for T. Thus the uncertainty with regard to N in these regions is not serious, because ν_c is so small.

By integrating the area under this curve we obtain

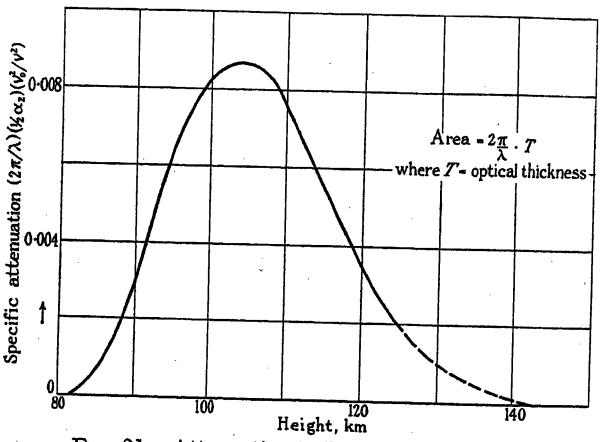


FIG. 21.—Attenuation in E layer ($\lambda = 22$ m).

the optical thickness corresponding to a wave of 22 m. T for this wave is 1·59 m.

From the known geometry of the rays the total exponent in the attenuation formula is known. It is approximately

$$\frac{2n\times 1\cdot 59}{\sin\theta_n}\times\frac{2\pi}{\lambda}$$

and becomes approximately 7·15 for 10 000 km.

We observe that $2\pi T/\lambda$ varies directly as λ^2. It is therefore reasonable to identify this with the limiting value of α_0, the effective attenuation coefficient at long distances. If we plot this on the α_0/λ^2 curve we find that the point is a little high. The value should be 6·2 instead of 7·15. Considering the uncertainty of the data the agreement is reasonably good, and we may feel confident that the residual attenuation α of the low-angle rays is caused by their passage through the lower attenuating E layer.

We have still to explain the high-angle attenuation. Having accounted completely for the E-layer attenuation we are forced to the conclusion that the F layer must be responsible for this attenuation. In the South African facsimile results, the maximum attenuation occurs at a time when the F layer density is a maximum, and not

when the E layer is. This constitutes additional evidence that the high-angle attenuation is caused by the F layer. The results imply that there is a certain residual attenuation in the regions where the rays are bent back to earth. The characteristics of such attenuation can be discussed in a general manner by considering that the density increases upwards and is sufficient at the greater heights to bend the rays to earth again.

A ray of shallow angle of elevation only penetrates the lower regions of the layer (where N is small) and the distance traversed in the layer is also small, so that the total attenuation is small. A higher-angle ray penetrates more deeply and has a longer path in the layer, so that the attenuation is greater. Thus in general the attenuation increases rapidly with the increase in angle of the ray. This appears to conform to the characteristics of the high-angle rays as observed. Again, shorter waves will, for a given angle, penetrate more deeply and have a longer path in the layer. In spite of the fact that the specific attenuation (per unit length) is reduced, the resultant attenuation, depending mainly on the depth of penetration and length of path traversed, increases with increasing frequency. The evidence as regards the variation of high-angle attenuation with frequency is very incomplete. Distant measurements determine $\underline{\alpha}_0$ only. The final field strength at a distance only depends on α_0. The value of α_0 therefore contributes nothing to the determination of high-angle attenuation.

The dip in the skip curve for waves above about 35 m (in daytime) where electron-limitation skip-effects cannot occur, should give information on this subject, according to the theory given in the author's previous papers, in which the skip in such ranges of wavelengths is attributed to the attenuation of the higher-angle rays. The fact that this skip region fills up on the longer waves is evidence of decreasing attenuation with decreasing frequency.

It is to be emphasized, in this connection, that in midday conditions the electron-limitation theory of the skip distance cannot apply to waves above 35 m (the critical wavelength corresponding to the maximum layer density $N_{max.}$). In this region we must use the attenuation theory of skip, which only holds good if there is attenuation in the F layer with the characteristics already discussed.

Using definite models of the F layer, the attenuation can be more definitely expressed. Thus if the gradient is constant the reflection coefficient is

$$e^{-\frac{4\pi}{3}(\sin^3\theta)m\Big/\left[\lambda^2e^2c^2\left(\frac{dN}{dz}\right)c\tau_c\right]} \quad . \quad . \quad (61)$$

where the quantities have their usual significance. If the density is proportional to the square of the height the reflection coefficient is

$$e^{-\frac{\pi(Z_0)_\lambda \sin^2\theta}{2c\tau_c}} \quad . \quad . \quad . \quad . \quad (62)$$

where $(Z_0)_\lambda$ is the depth of penetration into the layer at normal incidence on the wavelength λ. It varies inversely as λ. Both formulæ have the general characteristics (1) that there is a rapid increase of attenuation with the increase of angle of elevation, and (2) that there is an increase of attenuation with increasing frequency. These are the characteristics discussed above.

In the absence of any knowledge of the molecular density in the regions of the F layer it is hardly profitable to discuss the theoretical aspect of these results, but it might be worth while to determine roughly what average collision frequency is required to produce appreciable attenuation, and to see whether the figure comes within the bounds of possibility. Taking the second model, i.e. supposing that the density varies approximately as the square of the height above 200 km, and that the apex of the ray on the wave considered reaches a height of 300 km, so that $(Z_0)_\lambda \sin\theta \doteq 200$ km and, further, supposing that the reflection coefficient is e^{-2}, then the mean collision frequency required to produce this attenuation is 4×10^3, which does not appear to be an unreasonable value.

Appreciable high-angle upper-layer attenuation appears to occur at midday and on waves below 25 m. Skip-effects seem to imply that this attenuation is appreciable on the wave-range between 20 m and 70 m.

The F-layer attenuation is quite marked in full daylight conditions (A grade). There is insufficient evidence to determine how the layer attenuation varies diurnally, seasonally, and with latitude. Anderson's curves of the "Leviathan" on 75 m seem to show that it is small on this wavelength.

The author feels that he might be accused of picking out that material which fits best into the theoretical puzzle, if he did not exhibit or call attention to all the material impartially. In Table 7 all tne material is as far as possible treated in the same way, and values for $\underline{\alpha}_0$ and $\overline{\alpha}_0$ are obtained for the different seasons, different wavelengths, and different paths.

The observations on the stations Buenos Ayres (15·2 m), Cape Town (16·01 m), Poona (26·4 m), Cairo (21·7 m), and possibly Montreal (32·1 m), yield values of $\underline{\alpha}_0$ which fit into the scheme $\underline{\alpha}_0 \propto \lambda^2$, but the observations on the short 16-m to 20-m transatlantic stations definitely yield values of $\underline{\alpha}_0$ which do not fit in, being consistently larger, wavelength for wavelength, than the others. Can it be considered that this invalidates the conclusions drawn from the consistent observations?

It is to be remarked that the abnormal routes are also the variable and magnetically disturbed ones. The transatlantic great circles fall within the magnetically disturbed areas, if not within the auroral zone. It seems natural, therefore, to suppose that the abnormality is connected with this fact.

We have tacitly assumed, and justifiably in the author's opinion, that in the undisturbed regions the lowest-angle rays are unaffected by F-layer attenuation. It does not seem impossible that in the disturbed routes, i.e. transatlantic ones, this is not the case, and that there is still some residual F-layer attenuation even for the shallowest-angle rays; this seems the more probable on account of the fact that the abnormality is only present, or at least is more marked, on the shortest transatlantic waves, i.e. 16 m.

The facsimile record on Montreal taken during disturbed conditions lends support to this contention, for

it indicates that at such times high-angle attenuation is more excessive than in normal times. The disturbed areas have, it appears, greater F-layer attenuation than undisturbed regions, and apparently some residual effect remains even on the lower rays.

The overall attenuation on paths of mixed light and darkness is difficult to interpret. The apparent attenuation is low on normal all-dark routes, but again the transatlantic routes form an exception, for many high and irregular values of α are found in transmission when the route is wholly in darkness. The evidence seems to suggest that these transmissions are not only abnormally variable and subject to the effect of magnetic storms, but are subject to particularly high and variable

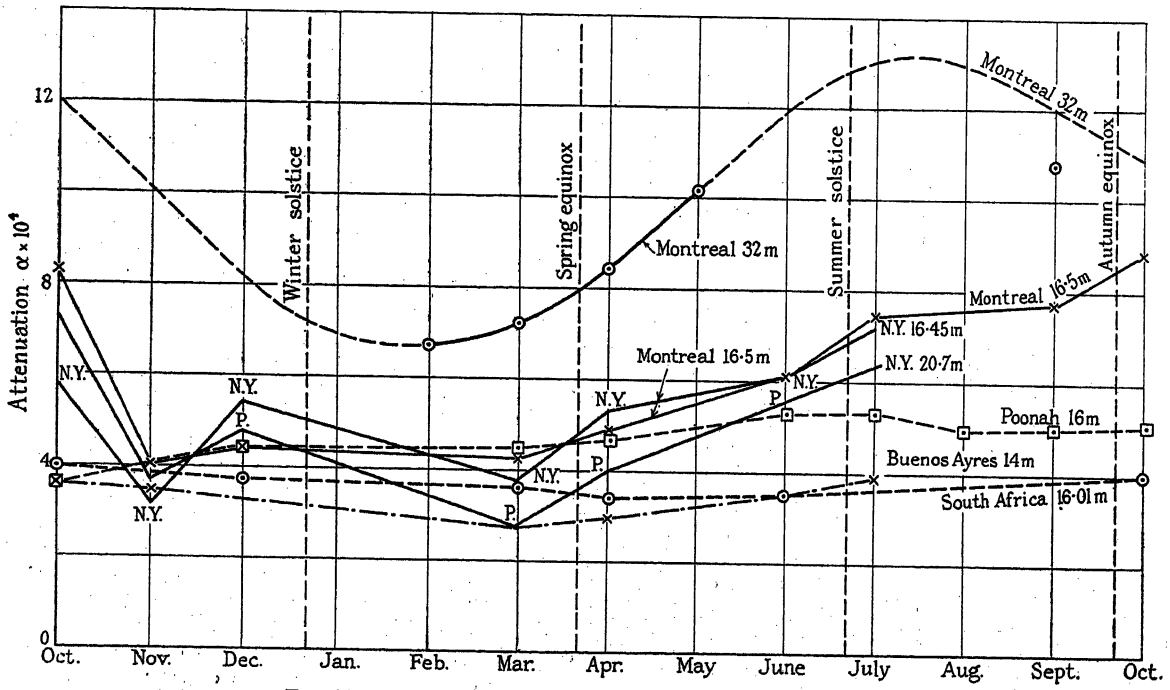


FIG. 22.—Seasonal change of maximum daylight attenuation.

able to analysis. It is, however, the more complicated cases that claim our attention when we are forced to consider the performance of any radio link. For this purpose K. Tremellen and the present author have devised a more comprehensive, if less accurate, method of determining these transmission characteristics. This has been published in the *Proceedings of the World Engineering Congress*, Tokyo, 1929. The method consists in employing a sort of weather chart of the Heaviside layer, which is of course related with the local time on the earth's surface, and moves round with the sun. This chart is marked with contour lines, like the isobars on a weather chart, which, for the night regions, give approximately the lines of equal maximum electronic density in the F layer. In the illuminated or day regions, the contour lines are more approximately those of equal density in the E layer, since it is the attenuation in this layer that is the main factor in transmission in daylight.

If the transmission characteristics on any given route and at a given time are required, the chart drawn on tracing paper is adjusted on top of a Mercator projection of the world, showing the great circle to be examined so as to represent the conditions in the Heaviside layer at the given local time, and then the radio conditions along the route can be read off at a glance. Separate charts are required for the various seasons.

The author does not intend to discuss this subject here in detail, except to show the bearing of the present measurements on the charts chiefly compiled from results obtained in 1928, and to point out the theoretical significance of these charts.

Originally started in a semi-empirical manner, always, however, with an eye to theoretical significance, they

F-layer attenuation. The two effects are in one sense the same.

The seasonal variation of daylight overall attenuation is shown in Fig. 22. This is most marked, of course, where the seasonal changes are greatest, i.e. in northern latitudes. There is practically no change on the South African route, as the mean conditions on the path are practically independent of season, half the path being in the northern and half in the southern hemisphere.

A feature which is rather surprising is that the conditions do not appear to be symmetrical about the summer and winter solstice. There is a sudden drop in the autumn and a slow rise in the spring. The results remind the author of the figure published in 1925* for the seasonal variation of field intensity of the long-wave transatlantic stations.

In the foregoing the author has picked out the simpler cases of transmissions which take place as far as possible in a uniform grade, so that the results should be amen-

* *Journal I.E.E.*, 1925, vol. 63, p. 943.

have become now in a great measure a real picture of the state of the maximum density in the Heaviside layer.

It is doubtful whether the charts could have been compiled if some theoretical guidance had not been forthcoming. With regard to the theoretical significance of the night contours, in the special case of the equinox chart near the Equator we have a means of checking these contours. From our experience of short-wave transmission we know the shortest wave that can be transmitted through a given grade. (The state of the layer between any two adjacent contours is denoted as a grade.)

Corresponding to a definite limiting wave, there is a definite maximum layer density. The times at which the various contours cut the Equator give the progress of the maximum density throughout the night. This ficant. Any marked change in the shape of the diurnal curve will be significant, but changes in the absolute values are not. This is because the charts, which give the final effects in R strengths, were not, until recently, finally calibrated in absolute measure. Some significant changes can, however, be noted. In particular the 32-m transmission from Montreal has been modified very considerably. Whereas, in 1928, signals throughout the winter nights were good for traffic handling, the observations in the winter of 1930–31 show that the signals drop to uncommercial values at midnight and do not become normal until after sunrise. On the other hand, day signals in the winter and spring months up to May, 1931, had a generally higher level than those measured in 1928. These results and other examples of the same sort suggest a secular decrease

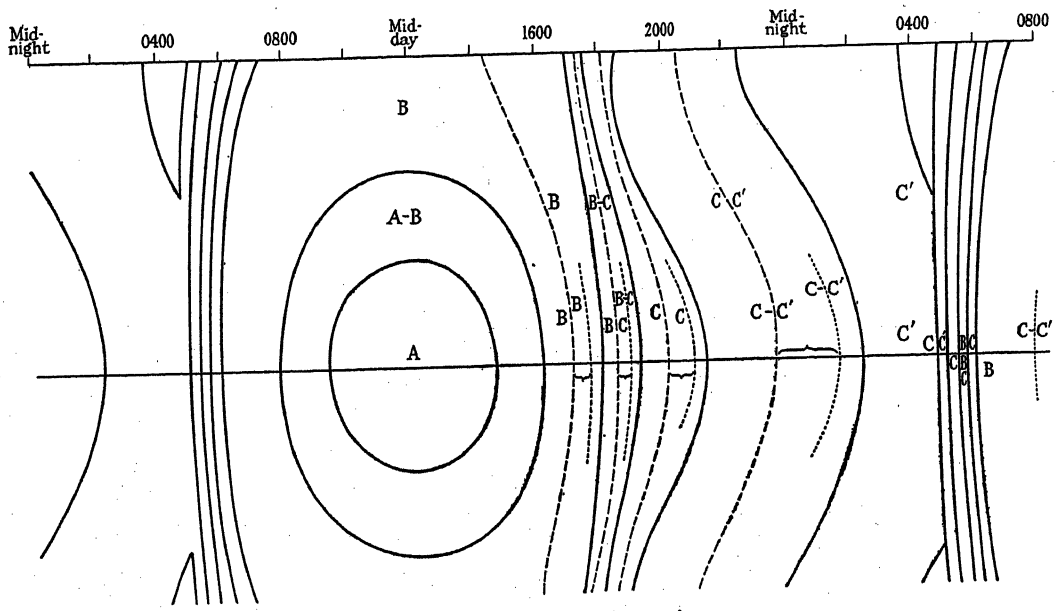


FIG. 23.—Shadow chart for equinox.

can be compared with either one of our recombination curves or with the theoretical curve calculated by S. Chapman.*

His calculation, with $\sigma_0 = 1$, corresponds closely to our case (equinox 1928). A comparison is shown in Fig. 23. The large dotted lines are the observed contours, the small dotted lines the calculated ones. The agreement is quite fair, considering the semi-empirical method by which the chart was compiled.

A result that follows from Chapman's analysis is that the positions at which the contours cross the Equator should be approximately independent of the season, and we find this fact reflected in our charts.

It would no doubt be an excellent exercise in the use of the charts to compare the actual diurnal signal curves with those deduced from the charts. The comparison should indicate any secular changes associated with the sunspot 11-year period that have taken place since 1928. Only those sufficiently large to swamp the uncertainty of estimation from the charts will be signi-

* *Proceedings of the Physical Society of London*, loc. cit.

of density in the F layer and a corresponding decrease in the E layer, giving less daylight attenuation. The first effect necessitates the use of longer waves at night to perform a given service.

Waves of 45 to 50 m are now required on the Montreal and transatlantic night service to do the work formerly done by the 32-m wave (1927–28). This secular change is reflected in the two diurnal density curves for 1929 and 1931 derived from facsimile results. The improvement in transatlantic day transmission on 32 m is not present in the 16-m transmission. This may be partly due to decreasing density in the F layer increasing the skip, and thus decreasing the available energy, but the author doubts whether this effect is sufficient, and he is inclined to attribute it to an increasing F layer attenuation. The 32-m E layer attenuation appears to have decreased, and we are driven to suppose that the 16-m transatlantic attenuation can only be increased in the F layer. Such an increase of attenuation in the F layer is possible even when the maximum density in this layer decreases, because the gradient probably decreases,

and therefore the penetration and, hence, attenuation are greater. This is shown in the formula

$$\text{Reflection coefficient} = e^{-\frac{\pi(Z_0)_\lambda \sin^2\theta}{2c\tau_c}}$$

The attenuation increases in proportion to Z_0, the depth of penetration into the layer. There is, however, an opposing factor in the fact that the penetration to greater heights brings the ray into regions where τ_c is greater or the collision frequency less, and thus tends to decrease the attenuation factor. Observation seems to show that the former is the controlling factor.

It needs boldness to predict the changes in short-wave transmission due to the secular changes in the Heaviside layer caused by the 11-year sunspot change. Nevertheless, the author is willing to court failure if such a prediction opens one's eyes to the significance of such changes as do occur, and leads to extended observations and tests of the theory.

The predictions are based partly on magnetic observations which, if correctly interpreted, give evidence for the secular changes of the density in the E and F layers. According to S. Chapman's magnetic evidence, the F layer has a large variation of N during the sunspot cycle, varying in parallel with, say, the sunspot numbers or associated magnetic storms. It varies irregularly from day to day by 20 per cent or more, quite independently of magnetic disturbance.

The E layer has a much smaller sunspot-cycle variation, but varies considerably from day to day in parallel with magnetic disturbances.

The effect of these changes on radio transmission can be gauged approximately in the light of the theory previously given. The conclusions are, of course, speculative, and perhaps the radio engineer would not be justified in altering his whole technique in accordance with them. However this may be, we are justified in deducing that the short-wave limit at any time, i.e. the wavelength at which the skip tends to infinity at this time, will vary in parallel with the phase of the sunspot cycle. The short-wave limit will be lowest at sunspot maximum and highest at sunspot minimum. As regards the percentage change in wavelength between the two extreme phases, we have as yet insufficient evidence, but the author feels that it may lie between 30 and 60 per cent.

The effects on attenuation are more complex, as both the E- and F-layer attenuations have to be considered. In a qualitative way the author would say that the E-layer attenuation should decrease between sunspot maximum and sunspot minimum to an extent of some 30 to 50 per cent, depending on the particular sunspot cycle. The F-layer attenuation probably increases, but this effect is more speculative and is based on observations separated by an interval of time, viz. 1928–31, which is small compared with the sunspot cycle. The effect of such changes in each individual transmission must be worked out separately, and too much space would be occupied in considering the various possible combinations of circumstances on all possible routes. Some examples, however, will illustrate the effects.

Thus, take the transatlantic transmission. A wavelength of 40 to 50 m will probably be satisfactory for night transmission but will be useless in daylight. A wave of 30 m will be too short for night transmission but will be a good daylight wave except perhaps in midsummer. A 20-m wave will probably be a good daylight summer wave. 16 m will still be a daylight wavelength, but of poor intensity, and its period of usefulness will be much reduced.

As another example consider the South African route. The midday communication is mostly controlled by E-layer attenuation. This should be improved at sunspot minimum unless F-layer attenuation begins to be effective. The shadow-band peak, which is mostly controlled by F-layer attenuation, will decrease towards sunspot minimum. The contrast in intensity between the shadow-band peak and the midday minimum, which is very great at sunspot maximum, should decrease towards sunspot minimum. We have, already, indications of this effect. The ratio of sunset peak to minimum midday signals at the end of October and beginning of November, 1931, is certainly less than the corresponding ratio at the same time in 1930. It may be possible to use a longer wave for day-working to South Africa during this phase of the magnetic cycle.

It is probable that the 34-m South African night-wave will be rather short for satisfactory working throughout the night, especially in our winter.

Summary of Part 2.

A very brief summary of these conclusions may help to focus attention on the salient features of short-wave transmission as disclosed by our results.

The material, consisting of a large number of measurements of signal intensities throughout the year 1930–31, has provided data for the analysis of transmission effects. Starting from the attenuation curves of the S.S. "Homeric," S.S. "Empress of Britain," and S.S. "Leviathan," we conclude that each one of the sheaf of rays transmitted is differently attenuated, and with the help of the facsimile results we conclude that high-angle rays are more attenuated than low-angle rays. The field intensity of a single ray was found to depend on two factors—attenuation and the focusing factor. Facsimile results and other theoretical considerations show that the focusing factor was practically proportional to the inverse distance.

The extreme variation of signal intensity could not be accounted for by variations in the focusing factor, and we concluded that the main factor in daylight transmission was attenuation.

Eliminating the magnetically disturbed routes (transatlantic) we found evidence that the overall attenuation α_0 was proportional to the square of the wavelength.

The overall attenuation on the disturbed routes was greater.

There was also some evidence of residual attenuation, even at night, although in the 75-m "Leviathan" transmission it was small. The low-angle attenuation α_0 was identified as the attenuation of the rays passing through the E layer, both for the reason that it varied in proportion to λ^2 and for the reason that the calculated E-layer attenuation agreed well with the observed. The

high-angle attenuation and the excess of attenuation in transatlantic transmissions was attributed to F-layer attenuation. Skip effects on wavelengths greater than 35 m show that residual F-layer attenuation should exist. This F-layer attenuation is shown to be more important on short than on long waves.

The secular changes in transmission between 1927–28 and 1930–31 are partly disclosed by the comparison of our recent results and those compiled from R-strength observations in 1928, and summarized in the form of semi-empirical charts, the theoretical significance of which was discussed.

These changes comprise an increase of limiting wavelength, a decrease of E-layer attenuation, and an increase of F-layer attenuation between sunspot maximum and sunspot minimum.

The practical consequences of some of these considerations is important.

The reasoning on which the raised-aerial experiment was projected in May, 1926, and described in the *Journal* (1927, vol. 65, p. 600) is fully confirmed.

Low-angle rays are least attenuated, and long-distance transmission is practically wholly effected by these. The use of a high beam aerial with a low projection angle (especially for the shorter waves) is therefore justified. If additional evidence of the effect of the angle of projection in the vertical plane were required, the evidence obtained by Bruce* would be convincing. Differences of the order of 15 to 20 decibels were obtained on two aerial arrays, one sharply directive at an angle of about 25° of projection and the other with a low angle of about 10° of projection.

Skip effects have not been discussed, but the evidence is conclusive that day skip effects on wavelengths greater than about 30 m cannot be due to electron limitations. For this region the theory of high-angle attenuation as outlined in the author's 1927 paper (quoted above) holds good, though the model of the Heaviside layer used was entirely wrong.

Directional effects, beam gains, etc., have not been discussed for want of space, although recent tests carried out in conjunction with the Post Office show remarkable results. Observations made last year show a considerable lateral bending of the South African beam at sunset, disclosed by relative field measurements at Chelmsford and Somerton, and by directional observations.

Finality cannot be reached until a whole sunspot cycle has passed, if then, but the data so far gathered have promoted a better understanding of the nature of short-wave transmission, as well as of the constitution of the Heaviside layer.

PART (3). SCATTERING.

Facsimile and signal-measurement results throw some light on the difficult subject of scattering. Although the author has no doubt whatever as to its existence, the origin, mechanism, and distribution of such scattering are still matters for speculation.

The clearest record of scattering is shown in the 60-m Writtle–Somerton ($d = 227$ km) facsimile photographs. Here we have definite evidence. A single, short impulse is spread out into a long trail of, may be, 20 milliseconds' duration. Such would be the record of a transmitted short signal which arrived by different paths, of lengths varying from 300 to 6 000 km. It is, however, only in rare cases that the scatter trail amounts to a 20-millisecond duration, a more average length being 10 to 12 milliseconds, indicating a scatter source at distances up to 1 500–1 800 km. This agrees with the results of triangulation given in the author's previous paper,* but the smudged signals do not show a well-defined scatter source, such as is indicated in some other scattering records.

The other facsimile results which show clear indication of scattering are records taken at Somerton on the 37-m Dorchester beam station. The distance of Somerton from Dorchester is 45 km. It is probable, but not certain, that this is less than skip distance at the time of observation, so that, except for the direct ray, the signal should be entirely scattered.

In two of the records there is evidence of scattering. Both records have this in common—that there is an irregular scattered signal of roughly 8 to 10 milliseconds' delay. In one case, however, the direct signal is followed, after 1·12 milliseconds, by a smudge of scattering lasting approximately 4 milliseconds. In the other this early scattering is irregular. Other effects attributed to scattering are shown, as already noted, on the 16- and 32-m South African facsimile records.

The identification of these signals as the effect of scattering is still open to doubt. Mögel* has recently discussed the quick echoes recorded at Geltow from the various local beams at Nauen. He attributes these effects to scattering, and employs the present author's theory of scattering in explanation. Records obtained by Hafstad and Tuve show complex echo patterns which are most naturally attributed to scattering. These complex echo patterns are not confined to what is usually known as the short-wave band, but are also indicated in observations made in the broadcast band on 1 400 kilocycles or 210 m.† There are now, in fact, records of scattering from 15 m upwards to 210 m.

Although it is perhaps generalizing on insufficient evidence, one cannot help being impressed by the fact that the shorter-wave scatter-echoes show a much more well-defined and more distant scatter source, and that where the receiver is beyond the edge of the skip distance the scatter signals do not, in general, start until after the first main reflection. These results may throw some light on the regions where the scatter signals originate. Take, for instance, the Dorchester records. It seems, since there is a distinct break between the direct signal and the first scatter signal, which is delayed about 1 millisecond, that the scatter source cannot be less than about 160 km from the receiver at Somerton. The only reasonable conclusion that we can draw is that the scatter source is in the Kennelly-Heaviside layer, some 160 km or more above the earth's surface.

Ground scattering cannot account for the absence of echoes of less than 1 millisecond delay.

The 60-m scatter signals are not so definite. It is

* *Bell System Technical Journal*, 1931, vol. 10. p, 661, Fig. 3B.

* *Elektrische Nachrichten-Technik*, 1931, vol. 8, p. 321.

† P. A. DE MARS, T. R. GILLILAND, and G. W. KENRICK : *Proceedings of the Institute of Radio Engineers*, 1931, vol. 19, p. 106.

difficult to trace a scatter signal back to its start, as other main reflection signals interfere, and the recording speed is insufficient for adequate separation. The author estimates that the gap between the first signal and the scatter signal is not greater than 0·5 millisecond.

In Hafstad and Tuve's experiments on 67 m* in disturbed magnetic conditions, the complicated echo patterns, which appear to be enhanced during such conditions, do not start until after about 2·5 milliseconds. Discounting the abnormal height (corresponding to 2·5 milliseconds) as caused by the increase in density of the lower E layer, these results would imply that the scattering source was in the neighbourhood of the apex of the rays—at some 200 to 250 km above the earth's surface.

On the other hand, in Mögel's oscillographic records of a 40-m scattered signal this overlaps with the main signal, and there appears to be less than 1 millisecond gap in agreement with the 60-m facsimile tests. The gap between the scattered echo and main signal is quite unequivocal on the shorter-wave records taken by Mögel, and agrees well with the definiteness of the scatter direction as disclosed by our direction-finding results. Such results are difficult to understand, since we should expect some intermediate delay echoes caused by the higher-angle rays penetrating the layer fairly close to the transmitter (and hence the receiver).

Earlier echoes may be absent on account of the absence of high-angle rays from the rather sharply defined beam projectors used in Mögel's experiments, but the present author is inclined to think that something of greater discrimination than this is required to account for the complete absence of shorter delay echoes, an absence which is very conspicuous in the records published.

When the regions above the 100-km layer are shielded by excessive attenuation, then, as in the 60-m tests, although the direct ray was of the same order of strength as at night the scattering disappears.

Taking all the evidence together the scattering source appears to be in the region of the Kennelly-Heaviside F layer above 100 km, but the evidence is rather indefinite and a good deal more material is required.

A large number of intensity measurements of scattered signals from the local beams have been taken during the course of the year's interception, and these also throw light on the scattering mechanism. The trouble in interpreting these results is that such a large number of alternative explanations are possible, and any inference tends to be more remote than one derived from pulse and facsimile measurements.

On a broad survey two points seem to stand out clearly. Firstly, the scattering fields from the shorter-wave stations are on the whole very much less than those from the longer-wave stations (i.e. up to 44 m). Secondly, the scattering from the denser grades A, A–B, etc., is very much greater than from the less dense grades C, C–C′, D, etc.

In order to free the observations from complications due to attenuation, and to obtain as far as possible the specific scattering power in various conditions, the data plotted in Fig. 24 were compiled. These are the monthly fields measured at 2300 G.M.T., when attenuation should be small, plotted month by month throughout most of the year 1931. The stations observed are in all cases beam stations, and the scattering direction close to 180°, i.e. back along the beam path. The wavelength range is 27·8 to 43·45 m. Although not very great this is sufficient to show a very marked change of absolute scattering power with wavelength. For every month the scattering region was associated with a definite grade in the layer which progressed from D to B (or B–C) as the season changed from winter to summer. The abscissæ can therefore be marked off in grades varying from D at midwinter to B–C at midsummer.

Individual peculiarities (directional, etc.) somewhat complicate the run of the curves, but there can be

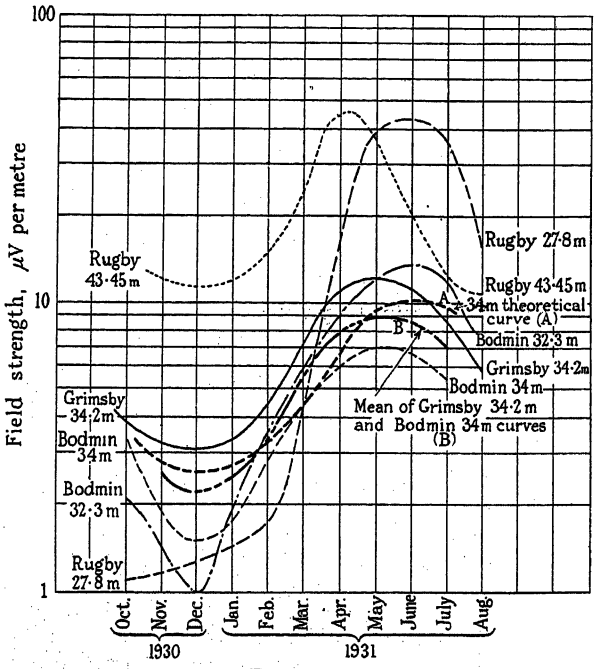


FIG. 24.

no doubt as to the general effects of the increase in grade density and wavelength. Similar conclusions can be drawn from the much more comprehensive but less accurate set of observations made during a year's interception in 1928, in which the estimated strength of a very large number of stations is recorded.

These results include many estimates of intensity of scattered signals. Those from the local beams have diurnal and seasonal characteristics which, when the effect of attenuation is discounted, show up very clearly the increase of intrinsic scattering with increase in layer density, and with increase of wavelength. The results of direction-finding experiments also confirm this, since the residual field strengths at the minimum are less on shorter than on longer waves. The effect here is not so marked, possibly because we are dealing with signals scattered forward, i.e. those for which the scattering angle is small.

There exists some evidence that the intrinsic scattering is increased during magnetic storms. This is confused

of the Institute of Radio Engineers, 1929, vol. 17, p. 1513.

by the effect of the increase of attenuation at such times, so that scattered fields may either be abnormally strong or abnormally weak. An analysis of the scattered fields shows, as a rule, abnormalities, but whether of increase or decrease cannot be stated.

Hafstad and Tuve's results show definite increase of scattered or complex echoes during a magnetic storm.

If the irregular, long-delay, facsimile echoes shown in the 16-m South African transmission are due to scattering as suggested, then the obvious correlation between these and magnetic storm conditions implies a relation between intrinsic scattering and magnetic disturbance. The evidence is suggestive, but not conclusive, a large amount of statistical material being required to establish a relation of this kind.

Theory.

A development of the theory given in the author's previous paper predicts results in general accord with these observations. In that paper it was suggested that ionic clouds of sufficient permanency would scatter the waves more or less in the manner observed. By tracing out the irregular scattering records in the 60-m facsimile tests it would appear that it is only necessary for the clouds to exist for fractions of a second, say $> 0{\cdot}02$ sec. but < 1 sec. We must imagine a state of turbulence in which these clouds are continually formed.

In the previous theory only the simple case of clouds small compared with the wavelength was considered. The author will deal here with the more general case of a spherically symmetrical cloud, which may be of dimensions large compared with those of the wavelength. One is led to consider such a case for the physical reason that such a cloud will offer little obstruction to the more penetrating higher-frequency waves, and will consequently scatter such waves back to a lesser degree than longer waves, in accordance with the observations described. The explanation will gain greatly in significance if the model can be made to explain the other main factor, i.e. increasing scatter with increasing average electronic density, without involving any further disposable constant. We shall be killing, theoretically, two birds with one stone. To analyse this case we have to start with the differential equation of propagation in the Kennelly-Heaviside layer, which is

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \frac{(2\pi)\nu_0^2 E}{c^2} = 0 \quad . \quad . \quad (63)$$

The effect of the cloud is introduced through the term $(2\pi)^2\nu_0^2/c^2 = 4\pi Ne^2/m$.

N may be considered to have a mean value N_0 together with a deviation δN which is a function of r, the distance from the centre of the cloud.

We therefore express the equation in the form

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - (2\pi)^2\left(\frac{\bar{\nu}_0^2}{c^2} + \frac{\delta\nu_0^2}{c^2}\right)E = 0 \quad . \quad (64)$$

Now consider E to be the sum of two parts—E_0, which is the original undisturbed wave, and which of course satisfies the condition

$$\nabla^2 E_0 - \frac{1}{c^2}\frac{\partial^2 E_0}{\partial t^2} - \frac{\bar{\nu}_0^2}{c^2}(2\pi)^2 E_0 = 0 \quad . \quad . \quad (65)$$

and E_1, which is the scattered wave, and can be considered as a small perturbation on top of E_0.

Equation (64) therefore becomes

$$\nabla^2 E_0 - \frac{1}{c^2}\frac{\partial^2 E_0}{\partial t^2} - \frac{\bar{\nu}_0^2}{c^2}(2\pi)^2 E_0 + \nabla^2 E_1 - \frac{1}{c^2}\frac{\partial^2 E_1}{\partial t^2} - \frac{\nu_0^2}{c^2}(2\pi)^2 E_1 = \frac{\delta\nu_0^2}{c^2}(2\pi)^2(E_0 + E_1) \quad . \quad (66)$$

the terms on the right being the small perturbation terms. The usual procedure, justified where the perturbation is small, is to neglect E_1 in comparison with E_0 in this last term, since $E_1\delta\nu_0^2(2\pi/c)^2$ is of the second order of smallness, and finally, since the first part of (66) containing E_0 is identically zero, we have the equation

$$\nabla^2 E_1 - \frac{1}{c^2}\frac{\partial^2 E_1}{\partial t^2} - \bar{\nu}_0^2\left(\frac{2\pi}{c}\right)^2 E_1 = \frac{\delta\nu_0^2}{c^2}(2\pi)^2 E_0 \quad (67)$$

where the form of E_0 is, of course, known, giving the scattered field E_1 in terms of the originating field E_0.

As we have stated, $\delta\nu_0^2$ is a function of r only. The choice of the function of r is to a certain extent arbitrary. The main features of the variation of E_1 with direction, wavelength, etc., will probably not be profoundly altered by alterations to the model, so long as this represents a cloud of finite extent and finite central density. In order to avoid excessive complications, we assume that the gradients in the cloud are so small that there is no necessity to take account of polarization effects.

The choice of the function representing $\delta\nu_0^2$ is guided by a very striking analogy with wave mechanics. It will be recalled that in a previous Institution paper,* and in a recent paper,† a dynamical interpretation was given to the ray transmission of electromagnetic waves in an ionized medium. It was shown that a pulse moved along a ray path as if it were a particle in a field of force derived from a potential proportional to the electronic density, i.e. analogous to a stream of, say, α-particles. Electronic clouds in such a medium are represented by a spherically symmetrical potential distribution, such as would be caused by charged atoms in the mechanical analogy. Such charged particles would scatter the original stream of electromagnetic pulses, or, in the mechanical analogy, α-particles. It follows, then, that the scattering of electromagnetic waves by electronic clouds is exactly analogous to the scattering of α-particles by heavy atoms.

The analysis of the scattering of α-particles by heavy atoms has been worked out according to the methods of wave mechanics. It is then found that the fundamental equation in this analysis has an exact formal analogy with (64).

A formula‡ is derived giving the ratio of the scattered

* "An Investigation of Short Waves," *Journal I.E.E.*, 1929, vol. 67, p. 992.
† "On the Connection between the Ray Theory of Electric Waves and Dynamics," *Proceedings of the Royal Society*, A, 1931, vol. 132, p. 83.
‡ A. SOMMERFELD: "Atombau und Spektrallinien," pp. 226-231.

wave function to the initial one in terms of the energy E of the particle, the atomic number Z, the radius a of the 1st Bohr orbit, etc. It is only necessary to translate these quantities into the corresponding analogous quantities in our problem to get a complete expression for the ratio of the scattered field E_1 to the original field E_0. In pursuing the analogy, it is assumed that the density distribution is proportional to $e^{-r/a}$, which is of the same form as (part of) the potential of an atom, and also that the gradient in the cloud is so small that questions of polarization can be ignored.

The extreme case, where the cloud is very small compared with the wavelength, has already been considered.

The intermediate case offers considerably more difficulties, and will not be considered here. The final form for the scattered radiation is, then,

$$\frac{E_1}{E_0} = \frac{(\delta\nu_0)^2}{c^2 r} \cdot \frac{1}{a} \cdot \frac{1}{2} \cdot \frac{1}{\left(\frac{1}{a^2} + K^2 \sin^2 \tfrac{1}{2}\theta\right)^2} \quad . \quad (68)$$

where $\delta\nu_0^2 = 8{\cdot}06 \times 10^7 \delta N$ gives the central density of the cloud ($r = 0$) over and above the mean density N_0, and a is the mean thickness of the cloud, i.e. the radius at which the excess cloud density is reduced to $1/e$ of the central density. $K = 2\pi/\bar{\lambda}$, where $\bar{\lambda}$ is the wavelength of the original radiation in the medium, i.e.

$$\bar{\lambda} = \lambda/[(1 - \lambda^2/\lambda_0^2)]^{\frac{1}{2}}$$

λ_0 being the critical wavelength for the electron cloud. θ is the angle of deviation of the scattered ray, E_1 the scattered intensity, and E_0 the original intensity.

It is easily verified that the expression on the right is a pure ratio, as it should be. The scattered radiation is, as is physically obvious, proportional to the central density. It varies inversely as the distance from the centre of the cloud, this acting as a secondary source. The final factor in (68) gives the polar diagram of the scattered energy, i.e. the relative energy scattered in different directions.

By hypothesis $a >> \bar{\lambda}$, so that the latter term in the denominator $K^2 \sin^2 \frac{1}{2}\theta$ is the dominant one for all values of θ which are not too small. The polar diagram is practically $1/(K^2 \sin^2 \frac{1}{2}\theta)^2$, and $\sin^2 \frac{1}{2}\theta$ varies from a small quantity, when θ is small, to unity, when $\theta = 180°$ (i.e. for back-scattering). We see that the energy scattered with small angular deviation is very large compared with that scattered backwards. The back-scattered intensity is proportional to

$$1/K^4 \quad \text{or} \quad \bar{\lambda}^4 \quad . \quad . \quad . \quad . \quad . \quad (69)$$

A typical polar diagram is shown in Fig. 25.

According to this theory, then, the amplitude of E_1 scattered back along a beam path, for instance, should be proportional to $\bar{\lambda}^4$. Now $\bar{\lambda}$ is not only a function of the wavelength *in vacuo*, but also depends on the mean value of λ_0, the critical wavelength—that is, on the closeness of λ to λ_0. $1/\bar{\lambda}$ is, in fact, proportional to the group velocity.

The formula, therefore, expresses the fact that the back-scattering is inversely proportional to the fourth power of the group velocity. This corresponds, in the analogous mechanical case, to the well-known fact that the slow α-particles are much more readily scattered than the fast-moving ones. It is clear, then, that a given inequality in density will produce the greatest scattering

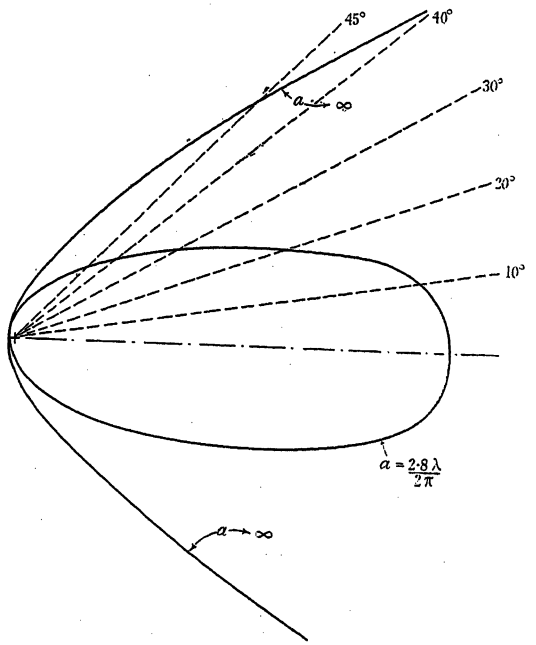


FIG. 25.—Polar diagram of scattering.

effect in the denser regions where the group velocity is smallest.

These deductions from the theory are significant in view of the evidence already cited. Thus, in the case where the intrinsic scattering is least confused by the effect of attenuation, we find, as shown in Fig. 26, that

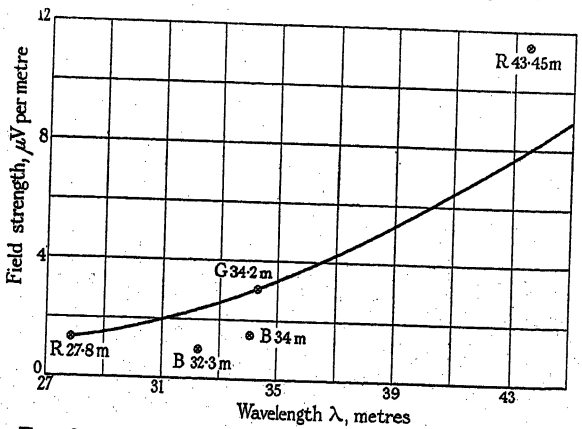


FIG. 26.—Fourth-power law (results obtained in 1930).

the intrinsic scattering increases rapidly with the effective wavelength. The theoretical curve proportional to the 4th power of $\bar{\lambda}$ is inserted for comparison. The results are in rough agreement. Too close agreement cannot be expected for the case of such a simplified model.

The effect of increasing layer density in increasing

the intrinsic scattering is also accounted for by this theory. We have, in fact, succeeded in theoretically killing the two birds with one stone. The maximum scattering should be in regions where the group velocity is a minimum (other things being equal).

In the experiments considered we are dealing with wavelengths so short that at the time (2300 G.M.T.) the layer is nowhere over-dense for such waves, and the group velocity never zero. In such a case the condition that $a > \overline{\lambda}$ can be maintained, and we can deduce that $E \propto 1/U^4$.

Now the maximum density in the different grades is approximately known. Taking a given wavelength, we can determine $U_{min.}$ corresponding to a given grade, and hence compute the relative intrinsic scattering intensities for the different grades. With the denser grades B–C the group velocity will be less, and the scattering greater, than with the less dense grades C′ and D. We have here the explanation of the increasing scattering effect of the denser grades as observed.

In Fig. 24 curve A represents the relative scattered intensity calculated in this way for a wavelength of 34 m, and curve B represents the mean observed variation of scattered intensity with grade for the two stations Bodmin (GBJ) and Grimsby (GBI). These two stations, working to the south and east, are least likely to suffer from the irregularities that may occur in regions to the north and west, which fall within the more magnetically disturbed areas. This model is able to explain the two main features of the observed scattered intensity, when undisturbed by the effect of attenuation. With extremely short waves the effect of scattering should be small (except for small deviations). The irregular echoes (of small deviation) of comparable intensity with the main echoes would thus be explained.

What happens at the other extreme of wavelengths is difficult to say. Experimental evidence is lacking, although a certain amount of scattering is indicated on the 120-m facsimile tests.

The analysis above is no longer applicable in this range because $\overline{\lambda}$ may tend to ∞, and the conditions will no longer hold. Effects of polarization will have to be taken into account, and if the wavelength becomes large compared with the mesh—as it may be called—(i.e. the mean distance between scattering centres) regular reflection or refraction will supervene. The effects of attenuation will become more marked, tending to blur the effects of scattering. The effects of scattering in such regions will be much more difficult to observe because there is no dead zone or skip zone, and scattered signals will be drowned by the main waves. Attempts to observe scattering with an Adcock direction-finding aerial on the 100- to 300-m region have failed, possibly for this reason. The complicated echo forms observed by de Mars, Gilliland and Kenrick may possibly indicate scattering in this range of wavelengths.

The obvious test of the theory is the comparison of the small-angle scattered signals with the back-scattered radiation. This comparison is, however, difficult to make because it is practically impossible to free the forward scattering from the effect of the main ray.

There are, no doubt, other alternative explanations of scattering effects, but the author has not found any that account for the facts so well—not one so generally in accord with the physical ideas of the general structure of the Kennelly-Heaviside layer. With regard to the manner in which the hypothetical clouds are produced, we can only venture the suggestion that the corpuscular ionization of the lower layer is irregular in both time and space. Extreme irregularities in ionization are exhibited in auroral displays, and it is not unreasonable to suppose that something of this kind, but on a smaller scale, produces the normal scattering clouds.

The apparent connection between scattering and magnetic activities then naturally follows.

PART (4). THEORY.

In Parts (1) and (2) of the paper the material derived from the facsimile and intensity measurements was discussed. By analysing this material we have formed a very definite, if not detailed, picture of the nature of short-wave transmission, and of the general features of the Kennelly-Heaviside layer. The picture of the latter is lacking in definition. The evidence discussed only applies to particular times and places. A complete picture would require much wider knowledge—a knowledge of the constitution of the conducting layer at all times and places. A sufficiently definite model of the Kennelly-Heaviside layer has, however, been obtained, from which, if correct, the main features of radio transmission should be deducible.

A physical picture of the processes of transmission is obtained by a consideration of the subsequent behaviour of the waves sent out by the transmitter. Let us consider, then, what happens to the waves after leaving this. In Fig. 3, T represents the transmitter and E the surface of the earth, while the Kennelly-Heaviside layer is represented by H. The waves leave T in all directions with intensities varying with the direction. Any wave at an angle of elevation θ can be considered to produce a secondary wave by reflection, refraction, or whatever it may be called, at the Kennelly-Heaviside layer, the phase and amplitude of the secondary wave being determined by the nature of the layer. The wave reaches the earth and is reflected again, and produces a zigzag of reflections between the earth and layer, of which we have a very concrete picture for short-wave transmission. If we fix our attention on a point some distance from the transmitter, the electromagnetic state is a medley of waves travelling in all directions, a state of confusion from which it would appear very difficult to make any calculated predictions. But there is really a certain amount of order in this state of confusion, and perhaps a simple example will be the best way of illustrating it.

A transmitter between two perfectly conducting planes, a distance h apart, is a very simple example of the above condition. The repeated reflections, as has often been explained before, can be represented by the effect of a series of images at a distance $2h$ apart, and the electromagnetic state in the region between the two layers is that produced by the row of virtual images. Now at great distances this row of virtual transmitters acts very similarly to a vertically stacked aerial.

If the height h is so small that the spacing between any two adjacent aerials is less than a wavelength, then

the whole behaves as a multiple aerial of the Franklin type, for which the transmission characteristics are well known, and the energy is wholly confined to the horizontal plane, the transmission in other directions being reduced to zero by phase cancellation.

It follows that where the height of the layer is $<\frac{1}{2}\lambda$, the resultant of all the complicated wave directions is horizontal, and we have a cylindrical wave transmitted horizontally between the two layers.

The confusion of other waves transmitted in various other directions disappears by phase cancellation. When the distance between the layers is greater than $\frac{1}{2}\lambda$ the effects are more complicated, but the solution develops on the same lines. Thus we still have a horizontally transmitted wave of the cylindrical type, but in addition

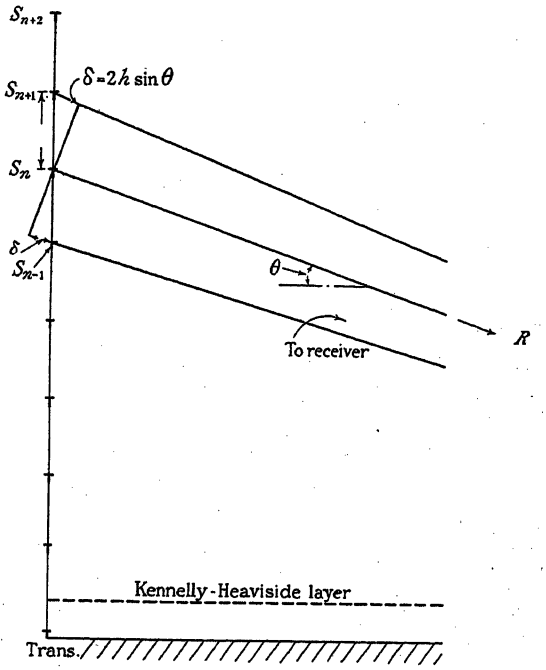


FIG. 27.—Image theory.

there are other favoured directions. These can easily be derived from the geometry of the system as follows: The rays (see Fig. 27) from the various imaginary images to a point situated at a great distance away from the transmitter are all very nearly parallel. Starting from R, for instance, we draw a line at an angle of elevation θ which cuts the row of images at S_n, say. The directions of the other rays, from R to S_{n-1}, S_{n-2}, etc., are practically parallel to RS_n. If now the distance $\delta = 2h\sin\theta$ is equal to a complete multiple of the wavelength, the e.m.f.'s from all the images near S_n are in phase, and therefore cumulative, so producing a finite effect at R.

The condition is that

$$n\lambda = 2h\sin\theta_n$$

or $$\sin\theta_n = \frac{n\lambda}{2h}, \text{ where } n \text{ is an integer} \quad . \quad . \quad (70)$$

This relation defines one of the possible directions. The number of possible directions is finite, since $\sin\theta < 1$.

If n_1 is the greatest integer which makes $n_1\lambda/(2h) < 1$, then n_1 is the number of possible ray directions, or "Eigen values," as we may call them on account of their connection with the quantum theory.*

This analytical result is not peculiar to this particular example. In all the cases of transmission between layers a set of Eigen values appears, and all that is necessary for their approximate determination is a knowledge of the change in phase and amplitude on reflection at the layer, whatever it may be.

The analysis given is of a rather elementary nature, but it is satisfactory to note that various mathematical investigations employing the wave theory with full analytical rigour exhibit the solutions in the form of a sum of terms, each representing a wave with an accurately defined direction θ_n, in fact a series of "Eigen waves" of the form

$$A_n\frac{1}{\sqrt{d}}e^{\frac{2\pi i}{\lambda}\cos\theta_n x - \alpha_n x} \quad . \quad . \quad . \quad . \quad (71)$$

Watson's theory of the transmission of waves round the earth is a particular case, and the solution found by him is the sum of a finite number of "Eigen waves" of this type, this number being the integer just less than $2h/\lambda$, exactly as in the case of the plane layer.

The definiteness of the Eigen values is probably marred by irregularities in the height of the layer, attenuation, etc.

A final steady state is also assumed, and transient phenomena may modify our conclusions. They nevertheless form a very real picture of the resultant effect of the criss-crossing waves in the region between the layers.

An analysis of this form applies throughout the whole radio gamut from the shortest wave that has a world-wide range—say 8 to 9 metres—to the longest. The picture thus obtained differs very considerably from the normal picture of short-wave transmission, in which the energy is transmitted along the geometrical rays—a picture which, we have seen, explains the observations very closely, and for which there is plenty of experimental justification. The question arises: Can these two views be reconciled?

For this purpose let us examine more closely the short-wave case as expressed in the Eigen function theory. We have seen that the field is expressed mathematically as the resultant of a number of waves travelling in definite and discrete directions. The number of these discrete directions is finite, and of the order of $2h/\lambda$. Now h may be 350 km for waves of the order of 20 m, so that $2h/\lambda$ is of the order of $2 \times 350/0{\cdot}02 = 35\,000$.

From the point of view of computing the field, this theory is of very little use. The resultant effect of these 35 000 different contributions is at first sight as difficult to compute as the original medley of criss-crossing wavelets.

Some further simplification is necessary, and this simplification leads to the ordinary ray theory. Thus if we examine the constitution of a ray, we find that it is analysable into a series of plane waves of slightly

* T. L. ECKERSLEY: *Proceedings of the Royal Society*, A, 1931, vol. 132, p. 83.

different wave-normals.* Thus, for instance, the expression

$$\Sigma A_n \cos\left\{\frac{2\pi l_n x}{\lambda} + \frac{2\pi m_n y}{\lambda} - 2\pi\nu t\right\} \quad . \quad . \quad (72)$$

where $l_n = l_0 + \delta l_n$, and δl_n is very small, considered as a function of x or y, can, by a suitable choice of the term A_n, represent a hump with maximum at $x = 0$, and the same for $y = 0$, and for all points on the locus of $l_0 x + m_0 y = 0$, so that the resultant is a ray travelling along the direction $l_0 x + m_0 y = 0$. Thus a group of plane waves travelling in directions slightly dispersed about $l_0 m_0$ produces a ray, and the converse is also obviously true. Now the original Eigen-value solution consists of a large number of plane waves of slightly different directions, and these can be built up to form rays. In any actual case, where reception takes place at R, say, the Eigen solutions will only sum up to form rays along those directions which in the ray theory join T and R with such rays. Thus the addition of all the appropriate Eigen functions for any particular case will form the geometrical rays of the ray theory.* It might be asked what is the use of deriving such well-known results in such a clumsy way, and the answer is, of course, that it indicates very clearly the failure of the ray theory for the longer waves. According to the above, the ray is more and more sharply defined as the difference in direction of any two adjacent wavelets becomes vanishingly small; or, put in another way, as the bundle of directions is contained in a vanishingly small angle, or again as the number of Eigen values tends to ∞, which it does as $\lambda \to 0$. As λ increases, the possible Eigen values become fewer and fewer, and the rays less and less sharply defined, and in the limit where the height h is only a few wavelengths the ray formation is entirely lost. In this we have the justification of the statement that the ray theory is not applicable in the long-wave range.

The transition region between the two classes of waves, i.e. those for which ray methods can be used and those for which they cannot, is, it will be observed, not sharply defined. It is therefore difficult to set a limit to the region of applicability of geometrical optics.

Apart from these considerations the Eigen-value theory will often give, by a simple method, the attenuation characteristics of each of the proper waves of which the ray is built, and therefore of the composite ray. This is often of considerable value, and, in general, avoids clumsy integration of the attenuation along the ray path. The characteristic Eigen values are defined essentially by the same methods as those which determine a ray, where such a ray can exist, and apply to cases where such rays cannot exist, for Fermat's method of determining a ray path provides that the path is such that the change of phase at the receiver is stationary for an infinitesimal change of path, and the proper directions are defined as those for which a group of reflected waves arrive in phase. The constant phase condition is common to both, and covers the determination of both proper directions and rays, where such exist.

* P. S. Epstein: *Proceedings of the National Academy of Sciences*, 1930, vol. 16.

The physical ideas which are the basis of the phase-integral method, and which determine the proper values, are really very simple, even in the general case. To simplify the matter still further, consider a region where the gradient of electronic density is wholly in one direction—let us say vertical. Where the gradients of density are not too great, so that the change of V/c is a small fraction in a wavelength (in the medium of the waves considered) the electromagnetic state, i.e. the solution of the equation of propagation, can be put in the form $e^{2\pi i S}$, where $2\pi S$ represents the phase of the wave at any point, and

$$S = \frac{1}{\lambda}\int \sqrt{\left[n^2 - (\nu_0^2/\nu^2)\right]}\,dz \quad . \quad . \quad . \quad (73)$$

where

$$\left.\begin{aligned} &n = \sin\theta,\\ &\theta = \text{angle of elevation of the ray,}\\ &\nu_0 = \text{critical frequency at a height } z, \text{ i.e. } \frac{N_z e^2}{\pi m c^2},\\ &\nu = \text{actual frequency,}\\ &\sqrt{\left[1 - (\nu_0^2/\nu^2)\right]} = \text{refractive index.} \end{aligned}\right\} \quad (74)$$

This relation may be derived directly from the differential equation, where gradients are assumed small, or from the more usual ray theory. It is simpler, as a matter of fact, to use the differential equation. This is

$$\frac{d^2E_z}{dz^2} + \left(\frac{2\pi\nu}{c}\right)^2\left(n^2 - \frac{\nu_0^2}{\nu^2}\right)E_z = 0 \quad . \quad . \quad (75)$$

when E is of the form

$$e^{\frac{2\pi i}{\lambda}my - 2\pi i\nu t} \times E_z \quad . \quad . \quad . \quad . \quad (76)$$

Supposing E_z is of the form $E_0 e^{2\pi i S}$, then the differential equation for S (neglecting $\nabla^2 S$, as we can when the gradient is sufficiently small) is

$$\left(\frac{\partial S}{\partial z}\right)^2 - \frac{1}{\lambda^2}\left(n^2 - \frac{\nu_0^2}{\nu^2}\right) = 0 \quad . \quad . \quad . \quad (77)$$

or

$$S = \frac{1}{\lambda}\int \left[n^2 - (\nu_0^2/\nu^2)\right]^{1/2} dz \quad . \quad . \quad . \quad (78)$$

It will be observed that the phase $\frac{2\pi}{\lambda}\int\left[n^2-(\nu_0^2/\nu^2)\right]^{1/2}dz$ is not a single valued function. The integral is only real between two adjacent roots of $n^2 - (\nu_0^2/\nu^2) = 0$. Let these be Z_1 and Z_2. The physical meaning of this is that the ray is confined to the region between Z_1 and Z_2. Outside this region the medium is over-dense for rays of initial angle θ ($\sin\theta = n$) and there is no penetration.

Now the difference in E at any two points A and B within this region Z_1 to Z_2 (Fig. 28) is

$$e^{\frac{2\pi i}{\lambda}\int_A^B \sqrt{\left[n^2-(\nu_0^2/\nu^2)\right]}dz} \quad . \quad . \quad . \quad . \quad (79)$$

but there is a certain ambiguity in this expression, for the quantity under the root sign, which let us call ζ,

may be taken as either positive or negative. The two values correspond to the phases of the resultant upgoing and downgoing waves respectively.

If we make the convention that when $\sqrt{\zeta}$ passes through zero it changes sign, then, integrating from A to Z_1 and back on the downward branch from Z_1 to A, we get the difference in phase of the upgoing and downgoing waves at A. But similar considerations apply at Z_2, where $\sqrt{\zeta}$ is again zero, so that if we integrate on the up-branch from A to Z_1 ($\sqrt{\zeta}$ positive), on the down-branch from Z_1 through A to Z_2 ($\sqrt{\zeta}$ negative), and then from Z_2 to A again ($\sqrt{\zeta}$ positive), we arrive back on the phase of the original upgoing wave at A, and at the original value of E.

But since

$$E = e^{\frac{2\pi i}{\lambda}\int\sqrt{[n^2-(\nu_0^2/\nu^2)]}dz}$$

then

$$E = e^{\frac{2\pi i}{\lambda}\int_A^{Z_1}\chi_+ dz+\frac{2\pi i}{\lambda}\int_{Z_1}^{Z_2}\chi_- dz+\frac{2\pi i}{\lambda}\int_{Z_2}^{A}\chi_+ dz} \qquad (80)$$

where $$\chi_\pm = \pm\sqrt{[n^2 - (\nu_0^2/\nu^2)]} \pm \sqrt{\zeta} \quad . \quad . \quad (81)$$

Now the sum of these integrals, i.e. from A to Z_1 (positive branch), Z_1 to Z_2 (negative branch), Z_2 to A

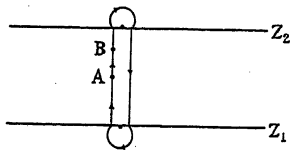


FIG. 28.

(positive branch), Z_2 to Z_1 (positive branch), and Z_1 to Z_2 (negative branch), is independent of the position of A, and is usually represented as $\oint\sqrt{[n^2 - (\nu_0^2/\nu^2)]}dz$, where the integral is taken round the branch points Z_1Z_2.

Now since

$$E = e^{\frac{2\pi i}{\lambda}\int\sqrt{[n^2-(\nu_0^2/\nu^2)]}dz}$$

$$= e^{\frac{2\pi i}{\lambda}\int\sqrt{[n^2-(\nu_0^2/\nu^2)]}dz+2\pi ri} \quad . \quad . \quad (82)$$

where r is any integer,

$$\frac{2\pi i}{\lambda}\oint[n^2 - (\nu_0^2/\nu^2)]^{1/2}dz = 2\pi ri \quad . \quad . \quad (83)$$

This is the phase-integral relation which determines the special values of n.

Examples of the use of this method are given in a previous paper* by the author. These examples can be worked out in any case where the phase integral can be evaluated.

In the previous paragraphs we were concerned in every case with vertical distribution of ionic density in which the simplifying condition holds, i.e. that gradients of density are everywhere small, or, as it may be more accurately expressed,

$$\frac{d}{dl_1}\cdot\frac{V}{c} \ll 1$$

where l_1 is distance measured in wavelengths in the medium, and the differential is taken along the maximum gradient of V. In many cases of long-wave transmission this condition is not satisfied in the medium, which is sharply graded (compared with λ). But where we are dealing with the transmission in the region between such a layer and the earth, it is still possible to use the phase-integral method if previously we know the phase-change at reflection at any angle.

Let $\delta\phi$ be this phase-change.

In the region between the earth and the Kennelly-Heaviside layer N is zero, and the contribution to the phase integral is

$$\frac{2\pi i}{\lambda}\int_0^h n dz$$

The contribution to the phase integral at reflection is $\delta\phi$, and from h to 0 again we have a contribution

$$\frac{2\pi i}{\lambda}\int_h^0 - n dz$$

The total is therefore

$$2 \times \frac{2\pi i}{\lambda}\int_0^h n dz + i\delta\phi$$

$\delta\phi$, of course, includes the amplitude change, and therefore the phase-integral condition is

$$\frac{2\pi i}{\lambda}2nh + i\delta\phi = 2\pi is \quad . \quad . \quad . \quad . \quad (84)$$

where s is an integer.

This is really the "flat earth condition." When taking account of the curvature the condition becomes

$$\frac{2\pi i}{\lambda}2\int_0^h\left\{1 - \frac{n(n+1)\lambda^2}{(2\pi r)^2}\right\}^{\frac{1}{2}}dz + i\delta\phi = 2\pi is \quad . \quad (85)$$

where $$r = R_0 + Z$$

determining unique values of n, which when substituted in

$$A\cos\left\{(n+\tfrac{1}{2})\theta - \tfrac{1}{4}\pi\right\}/\sqrt{(2\sin\theta)} \quad . \quad . \quad (86)$$

give the proper functions for the spherical case.

The first is generally sufficiently accurate for the higher-angle values of n, and the attenuation derived in the simple flat-earth case is generally very close to that derived by the more complicated formula.

Attenuation.

The phase-integral method leads, in the general case when α is small, to the same expression for the attenuation of a ray as is given by integration of the attenuation along the ray.

* *Proceedings of the Royal Society*, A, 1931, vol. 132, p. 83.

Starting from the general expression

$$\oint\left[n^2-\frac{(\nu_0')^2}{\nu^2}\right]dz=r\lambda \quad . \quad . \quad . \quad . \quad (87)$$

then when the effect of attenuation is taken account of

$$(\nu_0')^2=\frac{Ne^2c^2}{\pi m}(1+i\alpha)=\frac{\nu_0^2}{1+i\alpha} \quad . \quad . \quad (88)$$

where α is the factor which gives the attenuation, and is $\nu_c/(\pi\nu)$, ν_c being the collision frequency and ν the actual frequency. We will suppose that α is a small quantity, and of course a function of z, and we can therefore represent it as α_z.

Now

$$\oint\sqrt{\left[n^2-\frac{\nu_0^2}{\nu^2(1+i\alpha_z)}\right]}dz=\oint\sqrt{\left(n^2-\frac{\nu_0^2}{\nu^2}\cdot\frac{1-i\alpha_z}{1+\alpha_z^2}\right)}dz$$

and remembering that α_z is small, and neglecting α^2 compared with 1, we get, for the phase-integral condition,

$$\oint\sqrt{\left(n^2-\frac{\nu_0^2}{\nu^2}\right)}dz+\tfrac{1}{2}i\oint\alpha_z\frac{\nu_0^2}{\nu^2}\frac{1}{\left[n^2-(\nu_0^2/\nu^2)\right]^{1/2}}dz=r\lambda \quad . \quad (89)$$

We will suppose that n, the direction cosine of the ray (relative to the z axis) has a small imaginary part which of course measures the attenuation, so that $n=n_0+i\delta n_0$. Then the equation splits into two, one for the real and one for the imaginary part of n, i.e.

$$\oint\left[n_0^2-(\nu_0^2/\nu^2)\right]dz=r\lambda \quad . \quad . \quad . \quad (90)$$

and

$$\oint n_0\delta n\,dz/\sqrt{\left[n_0^2-(\nu_0^2/\nu^2)\right]}+\tfrac{1}{2}\oint\alpha_z(\nu_0^2/\nu^2)dz/\left[n_0^2-(\nu_0^2/\nu^2)\right]^{\frac{1}{2}}=0 \quad (91)$$

From the first we get the proper values n_0 (when we know the distribution function ν_0). For the attenuation coefficient in the direction y (along the ray) we require the corresponding value of δm, where m is the direction cosine in the y direction, and since

$$m^2=1-n^2, \quad m\delta m=-n\delta n \quad . \quad . \quad (92)$$

and

$$\delta m=-\frac{n_0}{m_0}\delta n$$

therefore

$$\delta m=-\frac{n_0}{m_0}\delta n$$

$$=\frac{n_0}{2m_0}\oint\frac{\alpha_z\frac{\nu_0^2}{\nu^2}dz}{\sqrt{\left(n_0^2-\frac{\nu_0^2}{\nu^2}\right)}}\Bigg/\oint\frac{n_0dz}{\sqrt{\left(n_0^2-\frac{\nu_0^2}{\nu^2}\right)}} \quad (93)$$

Now

$$\frac{dz}{\sqrt{\left[n^2-(\nu_0^2/\nu^2)\right]}}=\frac{cds}{c\sqrt{\left[1-(\nu_0^2/\nu^2)\right]}}$$

where ds is an element of the path, therefore $dz/\sqrt{\left[n^2-(\nu_0^2/\nu^2)\right]}=c\delta T_g$, where δT_g is the time a group takes in travelling the path δs, so that

$$\delta m=\frac{1}{2m_0}\oint\frac{a_z(\nu_0^2/\nu^2)ds}{\sqrt{\left[1-(\nu_0^2/\nu^2)\right]}}\Bigg/cT_g \quad . \quad . \quad (94)$$

where $T_g=\int dT_g=$ time taken by the group to travel along the path AB (a complete cycle).

Now $(2\pi/\lambda)\delta my$ is the total attenuation along the path AC (see Fig. 29). By the ray theory the actual time T_g taken by a group to travel along the path ABC

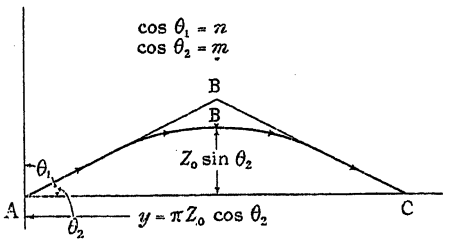


FIG. 29.

is the time taken by light to traverse AB_1C, so that $cT_g=AB_1+B_1C$ and $m_0cT_g=AC=y$.

Therefore the attenuation between A and C is

$$\frac{2\pi}{\lambda}\delta my=\frac{2\pi}{\lambda}\delta m\,.\,m_0cT_g=\frac{2\pi}{2\lambda}\oint a_z\frac{\nu_0^2}{\nu^2}\cdot\frac{ds}{\sqrt{\left[1-(\nu_0^2/\nu^2)\right]}} \quad (95)$$

This is

$$\oint\frac{\pi}{\lambda}\frac{\nu_c}{\pi\nu}\cdot\frac{\nu_0^2}{\nu^2}cdT_g$$

$$=\oint\nu_c\frac{\nu_0^2}{\nu^2}dT_g$$

$$=\oint\frac{\nu_0^2}{\nu^2}\frac{dT_g}{\tau_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (96)$$

where τ_c is the collision period.

In the case of a uniform medium, integration along the ray gives

$$\text{Total attenuation}=\frac{\nu_0^2}{\nu^2}\frac{T_g}{\tau_c} \quad . \quad . \quad . \quad (97)$$

which is essentially the same as the above.

The foregoing analysis, as in the previous case, refers to transmission in media where the change of V/c is small in a wavelength λ (in the medium).

Now in any case where the ray penetrates at normal incidence to regions near the critical density, $\lambda\to\infty$, and the above conditions cannot be fulfilled. It is, however, to be remarked that in the cases worked out rigorously by taking the solutions of the differential equations of transmission, the computed attenuations agree with those calculated by the phase-integral method (so long as α is small).

The two examples are:—

(1) A uniform gradient of $N\propto z$.
(2) A gradient proportional to the height, $N\propto z^2$.

We have proved the equivalence of the phase-integral method and the ordinary ray method as regards attenuation. Furthermore, the equivalence between the proper values and rays was discussed on page 445, where it was indicated that the rays of the ordinary ray theory could be built up of proper solutions. An illustration of this effect may give point to these considerations.

The rays of the ray theory are made evident in experiments, not by the optical method of locating them by means of a sharply directive receiver, but by inferring them from the time of arrival of pulses which are presumed to pass along the ray paths, because the delay time of such pulses is consistent with such inferences.

If now we can show by an example that the summation of a series of proper values appropriate to a given case gives rise to pulses whose time of travel equals that calculated by the ordinary group-velocity ray theory, then we can demonstrate the equivalence between the ray and proper-value theory.

The example is, in the nature of things, mathematical. The full details will, it is hoped, be published elsewhere. It is one in which the density is proportional to the square of the height.

The proper values for such a distribution are well known. Without going into details, we get for the sum of a number of these proper values an expression

$$E = e^{\frac{1}{4}C^2 - \frac{1}{2}\left(C\cos\frac{2\pi ct}{\pi Z_0} - z_1\right)^2} \times \cos\left[2\pi\nu t + C\sin\frac{2\pi ct}{\pi Z_0}\left(z_1 - \tfrac{1}{2}C\cos\frac{2\pi ct}{\pi Z_0}\right)\right] \times H_r\left[z_1 - \frac{C}{2}\left(\cos\frac{2\pi ct}{\pi z_0} + i\sin\frac{2\pi ct}{\pi z_0}\right)\right]. \quad (98)$$

where ν is the frequency, and Z_0 is the height at which the density reaches its critical value for this frequency. $H_r(x)$ is Hermite's polynomial of the order r for the argument x.

$$\left.\begin{aligned} Z_1^2 &= Z^2\left(\frac{2\pi\nu}{cz_0}\right) \\ C^2 &= \frac{2\pi z_0}{\lambda} \end{aligned}\right\} \quad \ldots \quad (99)$$

The factor that interests us is the first, which represents a very sharp peak in intensity travelling vertically at the group velocity $c\sqrt{[1 - (z^2/z_0^2)]}$, and takes a time $t = \pi z_0/c$ to reach the apex of its path and return to earth again. This is the correct group time for such an example.

A ray, also, may be represented by summing up a set of proper solutions. It is expressed by a function which has a sharp peak at the locus $z = z_0 \sin\theta \sin y/(\cos\theta z_0)$, which is the locus for the ray path calculated by ray methods. This is shown in Fig. 29.

The meaning of this is clear. The proper solutions, determined with close approximation by phase-integral methods, can be added together to represent the rays and groups of the ordinary ray theory in cases where the gradient is small enough. The proper solutions are accurate solutions of the differential equation. It is therefore shown that the rays and groups of the ordinary theory are the approximations formed by a set of proper solutions in such a case.

These results illustrate the equivalence of the two theories. The value of the phase-integral method, then, lies in the fact that mathematically the phase-integral relations are much more straightforward than the determination of the attenuation piecemeal by computing it bit by bit along the path, *and they can be applied to long-wave cases where rays lose their sharp-cut definition and are inappropriate to the problem.*

The failure of the ray representation can be attributed to the insufficiency of a number of proper values to build up a well-defined ray. This is especially the case in the E layer (below which long waves are confined) where the transition to the critical density (where there is no attenuation) on a 10-km wave is about 0·1 km, i.e. 0·01 wavelength.

Attenuation still further destroys the ray formation in the layer, since the energy diffuses outside the boundaries of the ray.

The author thinks that it may confidently be asserted that in the layer itself, when $\alpha > 1$ and the gradient is sharp, the flow of energy is *not* along rays, in the normal sense, and that even in the region between the earth and the Kennelly-Heaviside layer any rays that might be formed, by sharply directive projectors, for instance, are very ill-defined, and are inappropriate to give a mental picture of the mode of transmission.

In discussing transmission, then, so long as we confine ourselves to the short-wave range, say < 100 m, where $\alpha \ll 1$, the ray theory is adequate, with certain exceptions. These have been clearly stated by Hartree.*

The points on which the ray theory does not give an adequate account are enumerated below.

(1) Geometrical optics are inadequate to deal with propagation in a medium where there is an appreciable change of refractive index in a wavelength (in the medium). This occurs in the radio case where the waves penetrate to regions in which the density is near the critical value.

(2) The ray theory is inadequate to give account of the partial transmission through a thin over-dense layer. According to the ray theory, the ray is either completely reflected or completely escapes. It is an all-or-nothing effect. The true wave theory indicates that instead of an abrupt transition between these two cases, the process is gradual, so that we may get a partial reflection even where the angle is greater than the critical angle for reflection. This may affect the numerical calculations for the maximum layer density derived from facsimile measurements.

(3) In a stratified medium, waves polarized in and perpendicular to the plane of incidence are transmitted differently, and the ray theory takes no account of this difference.

(4) The ray theory is modified by the effect of attenuation, which allows energy to diffuse into regions which the ray theory forbids.

Apart from these effects, however, the geometrical tracing of the rays and the attenuation of these when α is small can be adequately treated by the methods of geometrical optics.

Proceedings of the Royal Society, A, 1931, vol. 131, p. 428.

With the mathematical method just described, and the model of the Kennelly-Heaviside layer disclosed in the previous section, we have the means at our disposal of calculating the transmission form for all waves in the radio gamut. We set ourselves this task at the outset, and although it is too much to hope that the task can be carried out in all detail, the general characteristics of transmission on all waves ought to be reproduced if the model is approximately correct.

For instance, we should be able to account for the fact that low-attenuation long-distance transmission is only possible at the extreme ends of the radio scale, i.e. the shortest and longest waves, and that the intermediate waves in the range, say between 100 and 1 000 m, are highly attenuated in daylight. We confine ourselves to daylight transmission so that in the first place the extra complication caused by magneto-ionic rotations can be avoided. This is justified at least to the first approximation, since the longer waves, which are chiefly affected by the earth's field, are confined to the regions where the collision frequency ν_c is large, compared with ν and with ν_1, the natural frequency of rotation of an electron in a magnetic field. The natural rotation effects are swamped by the irregular motions of collisions. In the lowest parts of the layer ν_c is of the order of 10^7, while ν_1 is $1{\cdot}41 \times 10^6$. Perhaps with extremely long waves in winter daylight in these latitudes this condition no longer holds, as such waves penetrate more deeply into the E layer, and the simplified theory is hardly adequate, but it may be considered as a starting point from which the deviations due to the earth's magnetic field can be calculated.

The short-wave commercial band, 14 to 50 m, has already been thoroughly discussed, and to avoid repetition we may extend our analysis both towards shorter waves and longer waves.

Starting with shorter waves than 14 m, the E-layer attenuation decreases with decreasing wavelength. This does not mean that signals over a given range will increase; this is because the main control of these short waves is by F-layer attenuation.

It is hardly accurate to give a definite mathematical expression for this attenuation in the absence of any precise knowledge of the density distribution and collision frequency in this layer, but an expression for this, using an idealized model (of the F layer) in which $N \propto Z^2$ and the collision frequency is constant, will epitomize the changes likely to occur.

The attenuation formula in this case is

$$e^{-\frac{1}{2}\pi z_0 \sin^3\theta/[\cos\theta(2h+\pi z_0 \sin\theta)]} \times \frac{1}{c\tau} \quad . \quad (100)$$

where Z_1 is the depth of penetration of the wave considered, θ is the angle of elevation, h is the height of the under surface of the F layer, and $\nu = 1/\tau$ = average collision frequency.

So long as h is greater than $\frac{1}{2}\pi z_0 \sin\theta$, for even the shortest waves, this quantity, being nearly proportional to z, increases approximately in proportion to the frequency. Part of this increase is discounted by the fact that with increasing frequency the average penetration increases, and the average value of ν_c, the collision frequency, becomes less. One would expect, then, the F-layer attenuation to increase gradually with decreasing wavelength.

The total attenuation, and the form of the α, ν curve, will depend on local time, season, and latitude, in a manner that cannot be exactly specified without further knowledge of the characteristics of the F layer, but the main characteristic will be a slightly increasing F-layer attenuation or, perhaps, nearly constant attenuation as the wavelength is reduced towards the short-wave limit. At the short-wave limit even the lowest rays penetrate the F layer and escape, and long-distance transmission is not possible.

According to the ray theory this process is abrupt. But we have seen that the ray theory gives an inadequate account of the partial transmission through, and partial reflection at or near, the limiting wavelength. The process is really gradual, bus probably abrupt enough to be very obvious. These transition phenomena have been discussed by Hartree * and H. Lassen.†

With glancing incidence Lassen computes that the transition region for the critical angle is only a few minutes of arc. If the critical angle is of the order of 10°, this implies that the percentage range of wavelength to cover the transition is only of the order of $\frac{1}{2}$ per cent or less, so that to all intents and purposes the transition is abrupt.

The wavelength at which the transition occurs has already been discussed. It depends on the minimum density of N on the route, and hence on the local time and season. For these latitudes for a route in the A grade the minimum wavelength is about 9–10 m.

In the ultra-short wave-band below this, we are dealing with the surface ray alone, which is determined chiefly by the geometrical optics of the visual range. It should be noted that some residual energy spreads into the geometrical shadow region. Its amount can be calculated by suitable diffraction formulæ.

G. N. Watson, Macdonald, Love and Nicholson have given such formulæ. In the most explicit, however (Watson's as amplified by Van der Pol), the exponential decrease is given in a form independent of the resistivity of the earth.

This is correct for waves which are long enough or of sufficiently high earth conductivity. Recently the author has been able, with the help of the phase-integral method, to derive the exponential factor in such a manner that the correction for earth resistivity can readily be incorporated. With a value of σ about 10^{-13}, resistance effects begin to be appreciable for waves under 3 km.

This matter is of importance in considering the transmission ranges of stations in the broadcast band in daytime, where reflection from the E layer is negligible and transmission is confined to the surface ray.

Longer Short Waves.

In proceeding upwards from the centre of the useful band, say 25 m, we reach two definite landmarks, one at a wavelength of 35 to 70 m (depending on the local

* D. R. Hartree: *Proceedings of the Cambridge Philosophical Society*, 1928–29, vol. 25, p. 97, and 1930–31, vol. 27, p. 428.

† H. Lassen and K. Försterling: *Zeitschrift für Technische Physik*, 1931, vol. 12, p. 453.

time) which marks the dividing line between waves that can penetrate the F layer at some angle of incidence and those which cannot do so at any angle; the other between 100 and 220 m, say, which marks a similar dividing line for the E layer. Conditions are not so definite here, however, because of magneto-optic effects, which may modify these conclusions.

There is one more critical wavelength which is of considerable theoretical, if not practical, importance. It is the wavelength at which even the horizontal ray penetrates the lower E layer. On account of the variation, diurnal and seasonal, of ionic density in this layer, it varies diurnally and seasonally.

It varies between the extreme limits $\lambda = 17{\cdot}5$ m for midday in midsummer in these latitudes, and approximately 40 m at late night periods.

Geometrically, a glancing initial ray which fails to penetrate the E layer is possible, but if we make an approximate calculation of the attenuation of such a ray we find that it is so large that it is unlikely that it can be received even over moderate distances.

In the section on long-distance signal measurement and on facsimile we have ignored this ray. We have, however, considered the possibility of such a ray in the case of the facsimile measurements. It leads, we saw, to the smaller values of τ_0, which from other internal evidence we considered to be unlikely. The justification for this neglect in the case of long-distance transmission is, as we have said, in the consideration of attenuation. We can trace the behaviour of the tangent ray from, say, 18 m upwards, in maximum daylight conditions.

It does not penetrate the E layer, and for wavelengths well above 18 m, say 20 m, the conditions may be considered to conform to the simplified model of the E layer disclosed by Appleton's experiments. In this model the electronic density starts to be appreciable at $h = 82$ km, and increases upwards as the square of the height above this datum.

To determine the attenuation, we require the distribution of ν_c, the collision frequency, as a function of the height. This may be obtained from Chapman's table.

If $(\nu_c)_0$ is the value at 82 km (the surface of separation) then $(\nu_c)_z$ (where z is the height above this surface) is $(\nu_c)_0 e^{-z/H}$ where H is the height of the homogeneous atmosphere. (For conditions in these regions $H = 9{\cdot}13$ km.)

We require also the depth of penetration $z_0 \times \sin\theta$ at an angle of incidence θ. This, in such a layer, is proportional to the frequency, as shown in Fig. 5 of Appleton's paper.*

For 20 m, at the tangent angle 10°, the penetration $Z_0 \sin\theta$ is $26{\cdot}5$ km and varies in proportion to the frequency. At 100 m, for instance, it is $5{\cdot}3$ km.

Using the phase-integral method, and neglecting the earth's curvature to the first approximation when h is small, we get the following expression for the attenuation coefficient:—

$$\beta = \frac{\frac{1}{2}\pi z_0 \sin^3\theta}{\cos\theta\,(2h + \pi z_0 \sin\theta)} \cdot \frac{1}{c\tau_c} \quad . \quad . \quad (101)$$

so long as $\alpha < 1$, where τ_c is the mean effective time between successive collisions over the trajectory followed by the ray. The shorter waves penetrate more deeply into regions where τ_c is greater and ν_c consequently less. The mean effective value of $1/\tau_c$ decreases rapidly with the frequency. An approximate expression for this quantity is obtained by taking the following weighted mean:—

$$\int_0^{z_0 \sin\theta} \frac{1}{c\tau_z}\frac{\nu_0^2}{\nu^2}dz \Big/ \int_0^{z_0 \sin\theta} \frac{\nu_0^2}{\nu^2}dz \quad . \quad . \quad . \quad . \quad (102)$$

thus giving most importance to the values of $1/\tau_c$ in the regions where N is greatest.

This leads to the expression [since $1/\tau_c = (1/\tau_0)e^{-z/H}$ and $\nu_0^2/\nu^2 = z^2/z_0^2$]

$$\frac{1}{\tau} = \frac{3}{\tau_0 D^2}\left[2 - e^{-D}\left\{(D+1)^2 + 1\right\}\right] = \frac{1}{\tau_0} f(D) \quad . \quad (103)$$

where

$$D = z_0 \sin\theta / H \quad . \quad . \quad . \quad . \quad (104)$$

Where D is sufficiently small, i.e. $Z_0 \sin\theta/H$ sufficiently small, $1/\tau \to 1/\tau_0$. This implies that where the depth

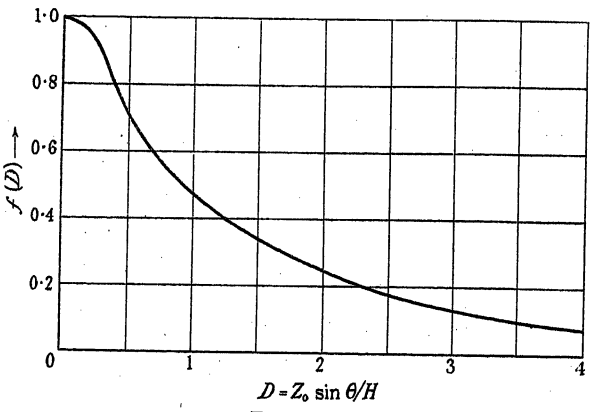


FIG. 30.

of penetration is small enough, only those regions are traversed where $\tau \doteq \tau_0$, and hence the mean value of T is practically τ_0. The curve showing $f(D)$ as a function of D is given in Fig. 30. For small values of D it is practically unity, but for large values, > 4, it is small and varies as $1/D^3$. This is because the rays penetrate the higher regions where ν_c is small.

The first factor

$$\frac{\frac{1}{2}\pi z_0 \sin^3\theta}{(2h + \pi z_0 \sin\theta)} \cdot \frac{1}{\tau_0} \quad . \quad . \quad . \quad (105)$$

represents what the attenuation would be, did the collision frequency not vary with the height. It illustrates the type of attenuation already described, where attenuation and bending both occur in the same layer. It is of the form $A\nu/(h + B\nu)$ and increases with the frequency, rapidly when $B\nu$ is small compared with h, but more slowly when $B\nu$ gets larger. Physically the increase has been attributed to the fact that the higher-frequency waves penetrate deeper and have longer paths in the layer, and are therefore more attenuated.

Taking account of the fact that ν_c decreases upwards, the total attenuation actually decreases with increasing

* *Proceedings of the Physical Society of London*, 1930, vol. 42, p. 328.

frequency, chiefly because the higher-frequency rays penetrate to regions where ν_c is so much less that this change more than compensates for the increase in the first factor. The total attenuation curve is plotted in Fig. 31. It is carried up to wavelengths of about 150 m. The formula does not adequately describe longer waves because it is based on the assumption that $\alpha = [\nu_c/(\pi\nu)]$ is a small quantity, and this assumption fails at the longer waves, where α becomes comparable with 1. The ordinates represent the decibel reduction (on account of attenuation) over a distance of 1 000 km.

This very large reduction, as calculated, seems at first sight rather surprising, but if we consider the matter in detail the reason for the large change is quite apparent. In Fig. 32 two rays are represented, one just longer and one shorter than the critical wavelength at which the nearly tangent ray just penetrates the E layer.

To cover a given distance the former has to traverse the E layer nearly 3 times as often as the latter. The attenuation on each traverse is considerably greater with the first than with the second. This is because the first traverses a long horizontal path at regions of the maxi-

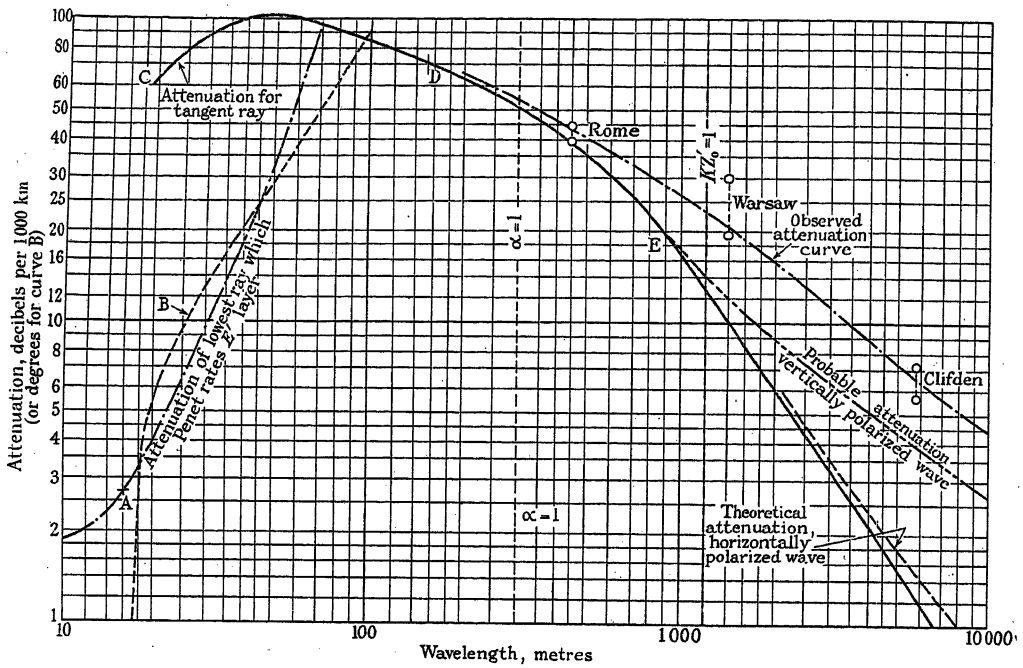


FIG. 31.

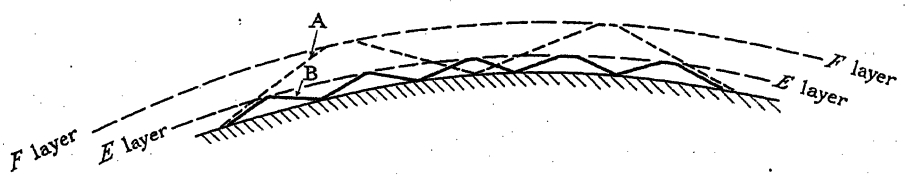


FIG. 32.—Comparison of two rays, drawn approximately to scale.
A.—Just penetrates E layer.
B.—Just below critical angle for E layer.

It is to be observed that even at the shortest wave (about 20 m) it is large, so that no appreciable long-distance transmission can be carried out by such rays.

A very rapid decrease in attenuation of the tangent ray occurs as the wavelength is reduced below the critical value of 17·5 m. It penetrates the E layer, and is transformed to one of the low-angle rays which is responsible for long-distance transmission.

The attenuation of such a ray, which is sufficiently below the critical value to proceed approximately without bending in the E layer, has already been calculated [see page 434 of Part (2), where the E-layer attenuation was considered]. It is represented by the point A in Fig. 31 for 16 m.

mum attenuation where N is near the critical density, and hence the overall attenuation of the first ray is very much greater than that of the ray which penetrates the layer, and which for large portions of its path is in high regions, where the attenuation is relatively small.

Thus when the tangent-ray attenuation curve (Fig. 31) is extended to shorter wavelengths than the critical one, there is an almost abrupt large reduction in the attenuation, which is still further reduced in proportion to λ^2 as the wavelength is decreased. The curve is therefore represented with an abrupt fall at C and continues along the branch of the λ^2 attenuation curve appropriate to long-distance E-layer attenuation.

Similar curves can be drawn for higher initial angles

of elevation. They do not reach their critical values until greater wavelengths are approached.

At such critical waves the attenuation abruptly increases to a value appropriate to the transmission of such rays as do not penetrate the E layer.

It appears that for long-distance day transmission it is necessary for the ray to penetrate the E layer. At night the minimum critical wave of this type is probably outside the normal working range for long-distance transmission (10 to 40 m), and normal transmissions are not complicated by this effect.

For any given wavelength above 17·5 m there is a critical angle for penetration of the E layer.

This angle/wavelength relation is also shown in Fig. 31 (curve B). Rays of angle less than this are useless for long-distance transmission. This may have certain practical consequences. If any engineer, going to extremes, were able to construct an aerial which confined all its radiation to less than this critical angle, he would be ill rewarded for his pains, for he would find that the energy radiated was useless for long-distance transmission. In the range of wavelength where long-distance daylight transmission is possible, say up to 30 m as an extreme, this vertical angle is so small that such an achievement is, if not impossible, very unlikely. On 25 m this angle is of the order of 9°, so that the angle of projection should be greater than this.

During magnetic storms the consequences of this effect may be serious. The density of the E layer may be considerably increased. For a given wavelength this will make the critical angle much greater (and also the attenuation of any rays which are below the critical angle). On the other hand, in such conditions F-layer attenuation sets in, which makes it necessary to use as low an angle of projection as possible. It is conceivable that the useful rays, i.e. those which penetrate the E layer, are still at such a high angle that they are severely reduced by F-layer attenuation. A reduction in wavelengths at such a time may be useful.

Extension to Long Waves.

We have drawn our tangent-wave attenuation curve as far as 150 m, where the attenuation shows signs of beginning to drop.

The region where α is in the neighbourhood of 1 is a transitional one, but even in this case the phase-integral method gives an answer to the question: "What is the attenuation for waves of different incident angles?" The formulæ are very complex, but become simpler again where we can assume $\alpha \gg 1$.

In any case where the rays are wholly confined below the E layer, as they are for all wavelengths greater than about 150 m in daytime, the attenuation increases rapidly with the wave angle, so that in practice we are confined to the tangent-angle wave. For wavelengths of 400 m and upwards we may assume $[\lambda/(2\pi z_0)]\sqrt{\alpha}$ not less than 1 in the region where the waves penetrate, and we have a simple form for the attenuation of glancing-angle waves. To determine it, it is only necessary to know the reflection coefficient of the layer. If we assume that $\lambda/(2\pi z_0')$ is sufficiently small, z_0' in this case being the depth of penetration multiplied by $\sqrt{\alpha}$, which may be a large quantity, we can extend a result given by Hartree,* in which the change in phase (including amplitude-change when α is complex) is

$$\delta\phi = \frac{\pi}{2} \cdot \frac{2\pi}{\lambda} \cdot Z_0^1 - \frac{\pi}{2} \quad . \quad . \quad . \quad (106)$$

Using this value, we obtain for the attenuation

$$\alpha = \frac{\pi^{3/2}(z_0)_{\lambda_1} \cdot \lambda_1 \nu_c^{1/2} \sin^3\theta}{2\sqrt{(2c)} \cdot \cos\theta h \lambda^{3/2}} \quad . \quad . \quad (107)$$

where $(z_0)_{\lambda_1}$ is the effective penetration at a wavelength λ_1, and $(z_0)_{\lambda_1}\lambda_1$ is a constant.

It will be observed that it decreases rapidly as the wavelength increases. ν_c can be considered to be approximately constant, since the depth of penetration is small compared with h. This branch of the attenuation curve is continued along DE.

It is possible to calculate other models. Thus, for the case in which N increases upwards exponentially, the reflection coefficient has been calculated by Elias.†

If the inductivity at a height z is $K_0(1 - \eta e^{-z/z_0})$ the reflection coefficient for vertically polarized waves is

$$e^{-\frac{2\pi z_0 \sin\theta}{\lambda\eta}} \quad . \quad . \quad . \quad . \quad . \quad (108)$$

Using the phase-integral method, we have

$$\beta = \frac{2\pi Z_0}{\lambda} \cdot \frac{\nu_c^2}{\nu_0^2} \sin^2\theta \quad . \quad . \quad . \quad . \quad (109)$$

where ν_0^2 is the value of $Ne^2c^2/(\pi m)$ at the surface of separation.

The reflection coefficient of a layer with uniform gradient has also been considered.

All the examples worked out have the following common characteristics:—

(1) The attenuation is some inverse function of the gradient of electronic density, so that the less the gradient the greater is the attenuation.
(2) The attenuation is in every case inversely proportional to the height of the layer above the earth.
(3) The attenuation in each case varies inversely as some power of λ. The longest waves are least attenuated.
(4) High-angle waves are in general much more attenuated than glancing-angle waves.
(5) The attenuation decreases with increasing ionic density (increasing everywhere in the same proportion).
(6) The attenuation increases with increasing collision frequency.

The characteristics of long-wave daylight transmission are included in this category, but modifications to the form appear when the wavelength is so long that the transition region in the layer is comparable with, or small compared with, the wavelengths. Further investigation of such cases is required, and the transmission of vertically and horizontally polarized waves is different. Nevertheless, the curve is continued along A at a slope

* *Proceedings of the Royal Society*, A, 1931, vol. 131, p. 144.
† *Elektrische Nachrichten-Technik*, 1931, vol. 8, p. 4.

of $-\frac{2}{3}$, according to formula. At wavelengths greater than 5 000 m, experimental evidence* shows that the slope flattens out to $-\frac{1}{2}$ (Austin-Cohen form). This is the extreme case where the transition layer can be considered to be quite sharp. The curve has been drawn to fall among the observed points for these regions. The characteristics of long-wave daylight transmission will be discussed more fully in a forthcoming publication.

The ultimate attenuation of ultra-long waves is a matter of some interest. If we continue the curve with the slope $-\frac{1}{2}$, then for waves of 100 000 km or more the attenuation appears to become very small indeed. Experimental evidence on the subject is wanting. The only experiment of which the author is aware was carried out by Round and Tremellen. Carnarvon station was used to transmit a 40-km wave, and was listened for by Tremellen in Australia. No signals were heard. Owing to the voltage limits of the aerial, the power radiated was relatively small compared with that used on its normal wavelength. This may account for the failure to receive the signals, or perhaps the violent atmospherics drowned the signals, but anyhow the experiment—inconclusive as it was—did not suggest excessively low attenuation. The author believes that there is sound theoretical reason for supposing that the curve flattens out and that the attenuation ceases to decrease at wavelengths above about 25 km.

The reason for this is connected with the fact that, both in the case of very long waves and in that of very short ones, the electromagnetic energy penetrates deeply into the layer where α is small or where practically pure refractive bending occurs. This was illustrated in Fig. 29 of the author's previous Institution paper, which shows the depth of penetration of waves into a uniformly graded medium as a function of the frequency. A similar curve (Fig. 33) can be drawn for a transmission layer in which N varies as the square of the height. The types of curve are very similar.

It will be seen that in the case of the very long waves the electromagnetic energy may penetrate deeply into the layer. In order to get an idea of the effect of variation of α with height, the simple case of a lower conducting layer $\alpha \gg 1$ bounded above by a purely ionically refracting layer $\alpha \ll 1$ is considered. When the energy penetrates the lower layer it is completely reflected internally by the upper layer. In such a case the effective resistance of the lower layer is constant and independent of the frequency, and the total attenuation is constant.

Considering the earth and upper layer to be a transmission line on a large scale, then the attenuation of waves guided by such a line is $e^{-(\rho/e)x}$, where ρ is the resistance for unit length of the outer conductors, i.e. the layer.

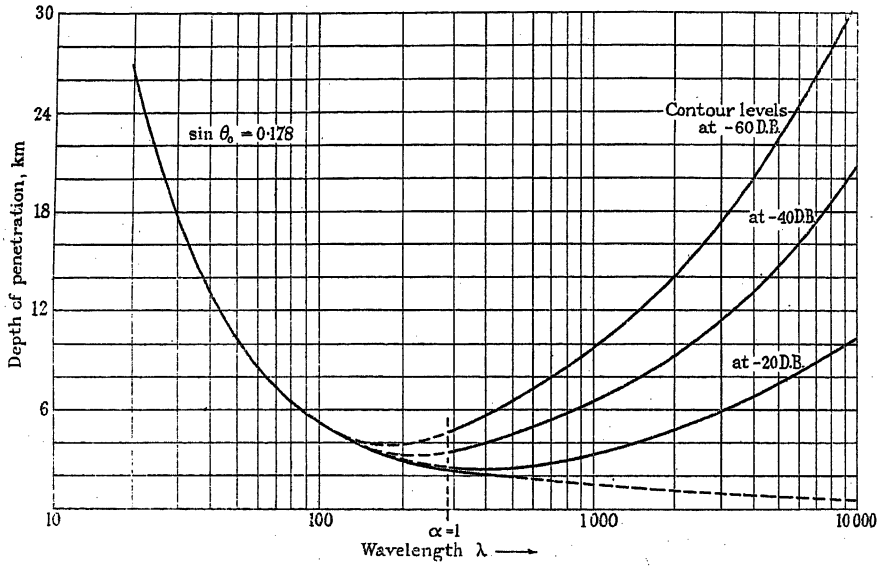


FIG. 33.—Depth of penetration (E layer) of tangent ray.

In this case the resistance ρ is constant, and the attenuation is constant. With higher frequencies the penetration is less (just as with an ordinary conductor the " skin effect " limits the penetration), in which case the effective ρ increases as the square root of the frequency, and we have the ordinary Austin-Cohen form of exponent, which varies as $\lambda^{-\frac{1}{2}}$. Physically, the improvement in long-wave transmission is due to the fact that with lower frequencies the effective resistance of the transmission line (i.e. the upper layer and earth) is decreased on account of the greater penetration of the electromagnetic energy. This improvement could only go on so long as the penetration increases with increasing wavelength.

Since the increased penetration brings the waves into a region where α is small and no further penetration can occur, the attenuation decreases no further and comes to a steady limit.

These considerations are, however, affected by the

* T. L. ECKERSLEY: *Journal I.E.E.*, 1925, vol. 63, p. 933.

fact that in the region where α becomes small, the reflection and penetration will depend on the magneto-ionic effects produced by the earth's magnetic field. The attenuation in this region will then depend on the direction of transmission relative to the earth's magnetic field, and on the state of polarization of the waves. Incidentally, these penetration curves give a very definite meaning to the overall daylight attenuation curve shown in Fig. 31. The very considerable peak of attenuation for waves in the broadcast band is associated with the minimum penetration in this region. From the transmission-line point of view, which, however, is only applicable so long as α is large, this should imply maximum attenuation, since on account of the small penetration the effective resistance of the layer is a maximum. The transmission-line point of view is a natural consequence of the application of the phase-integral method.

The task is finished, and, the author ventures to think, not unsuccessfully. The model of the Kennelly-Heaviside layer, disclosed by interference, facsimile, and signal measurements, has been found adequate to explain the main features of daylight transmission over the whole gamut of wavelengths from 9 m to 25 km.

Many details of the picture have yet to be filled in, and night transmission has been treated in rather a summary way.

The phase-integral method of attacking the problem has been used throughout.

The equivalence of this and the ray treatment for short waves has been demonstrated and the physical reason for the transmission characteristics has been discussed.

The absence of reflection of waves in the broadcast band is attributed, not to magneto-optical effects, which are so often invoked, but to the natural increase of the E-layer attenuation associated with the small penetration of waves into the layer on this band.

Reasons are given for supposing that magneto-optical effects are only of major importance at night, and perhaps on extremely long waves in the daytime.

The much more complicated case of night transmission remains. On the longer waves we have to take into account the direction of transmission relative to the direction of the earth's magnetic field, the state of polarization of the waves, and the gradient of ionic density.

This constitutes a problem of very considerable complexity. However, if the reflection coefficient of the layer can be found it will be possible to use the phase-integral method to determine the attenuation characteristics of the various possible types of waves transmitted over the earth's surface.

Acknowledgments.

In conclusion the author would like to take the opportunity of acknowledging his indebtedness to all those who have contributed to the production of this paper. It is a co-ordination of the results obtained by a group of workers—not by any means entirely an individual effort. K. Tremellen, as usual, has inspired many of the ideas recorded and has looked after the signal-intensity measurements made by the operators, Messrs. Davies and Salway, and analysed the material with respect to the effect of magnetic storms and the conditions in the Kennelly-Heaviside layer.

The facsimile results required a considerable amount of co-operation with the South African and Canadian companies. The author wishes to thank the Imperial and International Communications Co., and in particular A. McLellan and J. H. Thompson, for allowing suitable facsimile programmes to be sent.

R. F. Knight's task of making the facsimile measurements at Somerton was greatly helped by the facilities afforded by J. Brown. The analysis of the facsimile results by G. Millington and R. F. Knight involved the exacting task of measuring many hundreds of the echoes. Finally the author is indebted to Mr. Millington for the development of the method of analysis of these results which is given practically in his words in Part (2) of the paper.

Discussion before the Wireless Section, 23rd March, 1932.

Mr. L. B. Turner: Two points which impress me in connection with the paper are the complexity of the physical conditions involved in the long-distance propagation of short-wave signals, and the difficulty of establishing sufficient contacts between the theory and the available experimental observations to enable the latter to serve as a check upon the theory. Our experimental contacts with the upper atmosphere are made by launching a signal into it and observing the echo which returns. The simplest form of the experiment consists in directing the signal almost vertically from the transmitter, and receiving the echo at a point very near to the transmitter. In the hands of Prof. Appleton and others, this method has provided very definite information about the nature and height of the Kennelly-Heaviside layer at that point. The author has made use of a different method. In his experiments the signal does not return to its starting-point; instead, multiple reflections occur between the ionized layer and the earth. After being reflected n times a ray arrives at the receiving station, where it forms only one part of the total received signal: this consists of the echoes of the 1st, 2nd, . . . nth, . . . mth orders. All these echoes are recorded on the film, and it is mainly the relationship between them upon which the author relies to obtain information about the Heaviside layer. While the kind of measurements that the author has been using are of direct practical application to facsimile transmission, as a method of research into the nature of the Heaviside layer they seem to be open to many important objections. In the first place, the condition of the layer varies widely with the diurnal cycle, depending upon local time; and as the reflections are instantaneous, they occur at different places at different values of local time. It must be supposed that even if the condition of the whole of the Heaviside layer is the same at any one specified local time, it is not the same at the various places where the multiple reflections occur. Secondly, is the first signal received the ray which has undergone one or two reflections at the upper layer? The first-order ray is perhaps diverted

by the lower layer and so is not registered. Thirdly, is the last recorded ray really the last because all rays of higher angle penetrate the layer; or is it the last because rays of higher angle are attenuated too much to be observed on the record? This point is important if we are to deduce the maximum electron density in the layer. The difficulty of answering these questions seems to necessitate rather bold and dangerous guesswork, and renders facsimile transmission a somewhat unsatisfactory means of investigating the Heaviside layer. As regards Fig. 5, it may be noticed that a nearly horizontal straight line would fit the observations just as well as the lower curve drawn; and in Fig. 7 the observed points are not shown at all. The author makes no reference to Appleton as the discoverer of the upper Heaviside layer. Appleton and Barnett* in 1925 raised the accepted height of the then only known layer from 40 to 100 km, and the first suggestion of a second reflecting layer at a height of 250 to 300 km was made by Appleton in September 1927.†

Prof. S. Chapman: Despite the difficulties to which Mr. Turner has referred, the author's results concerning the nature of the upper layer appear to agree with those derived by Prof. Appleton's more direct method. The fact that the results show a great difference from one year to another, perhaps owing to the effect of the sunspot cycle, is of great interest. It is paralleled by the inferences arrived at from terrestrial magnetism as to the variation of solar emission according to the sunspot cycle. However, although part of the sun's radiation changes very greatly in this cycle, the radiation which we receive on the ground and on which human life depends seems to be constant. I hope that a good deal more information will be derived from radio measurements in the future regarding the electron-density gradients in the upper and lower Heaviside layers. Such measurements would indicate the attenuation of the atmosphere with height, and also the temperature distribution in the atmosphere. This information seems to be obtainable in no other way.

Mr. G. Millington: I should like to compliment the author upon the large amount of valuable information he has obtained from experiments which have been necessarily rough owing to the fickleness of the Heaviside layer. As regards the variation of ionic density with local time, a generalized extension of the comparison suggested in Fig. 23 between empirical and calculated charts shows that the agreement is very good in the tropical regions and especially in summer. Although the calculation of the charts involves a number of assumptions, the general accuracy is amply sufficient to show that in addition to that produced by the assumed ultra-violet radiation there is some extra ionization in the higher latitudes which extends into the polar regions. The slide which I propose to exhibit shows a winter chart redrawn on a circular projection with the North Pole in the centre. The empirical charts suggest that the contour lines should all be pushed up much closer to the pole, and it is impossible by any adjustment of the constants of the theory to make the calculated charts fit the facts for all latitudes. Tremellen has made some observations in the winter months on the signals from various stations to determine at different local times whether the stations are inside or outside the skip distance. The results obtained so far are only of a preliminary nature, and a more systematic series of observations is being made for the equinox season. We have been able, however, to plot an experimental curve giving the variation of ionic density with local time at latitude 50° N. and from it to estimate the amount of the extra ionization. It appears that it also varies diurnally with the sun, and that the ionizing agent produces three times as many ions as the monochromatic radiation which would produce the observed ionization at the equator. The forthcoming polar expedition will be anxiously watched to see whether this rather striking value is of the right order.

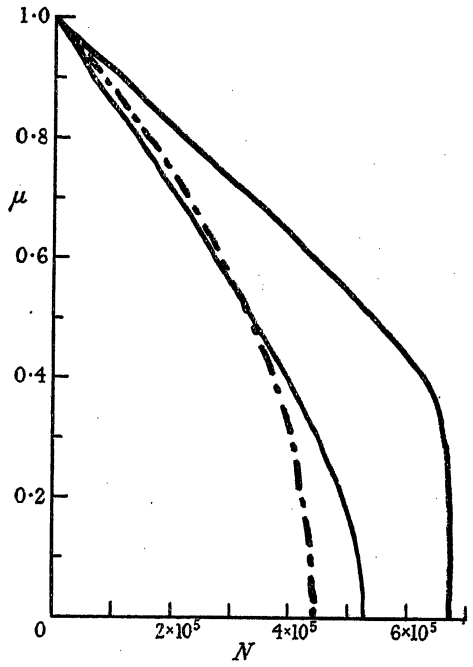


FIG. A.

Magneto-ionic theory.
Formula given in paper.

Dr. J. Hollingworth: I should like to endorse the author's remarks on page 425 as to the conditions necessary for satisfactory observations; but at the same time I feel that by starting with a preconceived theory one runs the risk of drawing deductions which may not be fully justified. In my opinion the value of pure statistical methods for dealing with such a complex subject is not great. Throughout the paper the expression " ray angle " is used to denote the angle which the arriving ray makes with the horizontal. Physicists are more accustomed to deal with the complement of this—the angle of normal incidence—so that it is necessary to state the matter very definitely in order to avoid confusion. I do not agree with the statement that the effect of the earth's magnetic field is not very serious on short waves. In Fig. A I have drawn curves for the relation between the equivalent refractive index μ and the ionic density N. The dotted curve is the one given

* *Nature*, 1925, vol. 115, p. 333. † *Ibid.*, 1927, vol. 120, p. 330.

by the formula in the paper, whereas the full-line curves are obtained from the magneto-ionic theory as developed by Appleton and Hartree. In each case the frequency is 6 megacycles per sec., the direction of transmission being at an angle of 80° to the magnetic meridian. The doubling of the full-line curves arises from the double refraction inherent in the magneto-ionic theory. It will be seen that the author's curve agrees fairly closely with one branch but diverges considerably from the other. While for a general explanation the single curve is ample, when it comes to deciding whether a given ray will or will not be returned and from which layer, the inclusion of the effect of the earth's magnetic field is essential. I am interested in the idea of a " long-hop " ray (Fig. 10) because I myself have been driven to the same conclusion by recent experimental observations. The chief point on which I differ from the author is that of the relative amounts of energy in the short and long hops, as my experiments distinctly show that the majority of the energy may be returned at surprising large ray angles. My results are based on the diagrams obtained from a cathode-ray oscillograph using closed coils. With this arrangement the " cross-field," i.e. the one which produces a deflection on the cathode-ray tube at right angles to the direction of propagation and thus gives rise to the well-known ellipse, is proportional to the sine of the ray angle. All my observations have shown that the outstanding feature of this ellipse is its fatness, a characteristic which can only be explained by one of two alternatives. Either the horizontally-polarized component of the electric field is much larger than the normal vertically-polarized component, which seems most unlikely, or unexpectedly large ray angles may occur. The former alternative can be eliminated by aerial-coil observations, and using this method it has been found that on a station at a distance of 2 500 km a ray angle of 60° is by no means uncommon.

Mr. G. Builder: I do not think the author's method is suitable for investigation of the Heaviside layer. To anyone who has seen the complexity of echo patterns on short-distance transmissions when there is a ground wave present, it is surprising that the author should have succeeded in interpreting his results. As regards the question of nomenclature, the term " Kennelly-Heaviside layer " is best restricted to the lower layer; to distinguish one layer from the other Prof. Appleton applied the letters E and F to the lower and upper layers respectively. It is necessary to consider other possibilities than scattering to account for the observed results. Last year Prof. Appleton and I came across the phenomenon of the splitting of an echo into two components, and we have ascribed this to the effect of the earth's magnetic field. The simple splitting was predominant throughout the summer, and then turned gradually into a multiple-splitting effect. The two components of a single echo each seemed to split, and later on in the year the components became very complex, causing a " smudged " echo. Working on short-wave transmissions of from 30 to 150 metres, the smudged echo from the upper layer may last as long as 3 milliseconds; considering the distance, this is probably comparable with the duration of the scattered echoes to which the author refers. If the explanation of the simple splitting of the echo is correct, multiple splitting must be a magneto-ionic effect, and it would appear to be applicable to some of the American results quoted in the paper. Its exact applicability to the shorter waves is not at all clear at present. As regards the question of whether or not the F layer is stratified, there is a suggestion that the F layer consists of two strata, the one of greater ionic density being the higher. Measurements of the equivalent height of the layer on a single wavelength, however, provide no evidence of a sudden jump to a higher level. The curve of equivalent height against time proceeds smoothly until such time as the electron limitation allows the wave being used to penetrate the layer, and no more echoes occur until ionization commences again in the morning. Turning to the variation of the height of the layer with wavelength, the data available provide no definite evidence of any discontinuity in the curve representing this relation, and consequently there appears to be no justification for assuming that the layer is stratified. The idea of a lower F layer formed by the ionization of nitrogen and oxygen molecules does not seem sufficient to account for a layer of greater ionic density than the lower E layer. The author gives ionization curves of the upper layer in which much of the curve is filled in by interpolation, using Prof. Chapman's theory. During the last 6 months Prof. Appleton and I have been making accurate determinations of the ionic content of the upper layer at short distances, and the curves which we have obtained are not generally in agreement with those given in the paper—probably because the author's method is unsuitable for accurate investigation of the ionized layers. There is some indication of ionization of the upper layer during the night, with definite increases in ionization after midnight. The values which we have obtained for the ionization could just as well be fitted to the author's results as have the curves given by Prof. Chapman. At close ranges the echo method is definitely superior in accuracy to facsimile measurements. With regard to the term " critical frequency " (page 411), in my opinion the expression " critical penetration frequency " would have better expressed the author's meaning.

Mr. J. F. Herd: It is interesting to find that the author is now in complete accord with Prof. Appleton in his acceptance of the idea of two layers. As regards the measurements described in the paper, the author has succeeded in extracting a remarkable volume of fact from a mass of somewhat unpromising data. For the purpose of *ad hoc* measurements of layer height, ionic densities, etc., it is very doubtful, however, if such long-distance observations will ever be able to yield as much valuable information as short-distance observations which include the ground wave as a rigorous reference. It is certain that in a complete picture of propagational phenomena the effect of the earth's magnetic field must be taken into account. Reference has already been made in the discussion to differences between polar and equatorial latitudes; valuable information on conditions within the Arctic Circle should become available from the programme proposed by the Radio Research Board in connection with their polar year observations

which are to begin in August 1932. The systematic work proposed consists of the measurement of layer heights and ionic densities. The methods used will include both the " frequency-change " method due to Appleton and the " short-pulse " method first suggested by Breit and Tuve. In addition to using the returned echoes for determination of heights and densities, it will probably be possible to study the polarization of the downcoming components.

Mr. T. L. Eckersley (*in reply*): My critics appear to have overlooked the title of the paper, or they would have realized that it is concerned with the elucidation of short-wave long-distance transmission rather than with a direct investigation of the Heaviside layer. I admit that direct study of the Heaviside layer is an integral and essential part of the study of short-wave transmission, but my firm conviction is that the greatest advance can be made by studying each part separately, in fact, by analysing each part in the most direct and simple way possible. The vertical-pulse method is one of the most direct methods of analysis and gives interpretable results, but, unfortunately, it is not the most direct method of determining the part played by the Kennelly-Heaviside layer in long-distance transmission, which employs, almost exclusively, glancing angle rays and not vertical ones. In consequence, when the paper is considered as an organic whole, and when the first section is considered in its relation to the solution of the problems in the remainder of the paper, it appears to me that the facsimile method is quite suitable in spite of its admitted drawbacks, which are pointed out by Mr. Turner and also in the paper itself. I question whether any alternative is possible. This suitability is made more clear when we realize that information given by vertical pulses is confined to the behaviour of waves sufficiently long to be refracted at normal incidence, i.e. waves usually greater than 35 to 40 m, while long-distance transmission is practically entirely confined to waves shorter than this. If the behaviour of the shorter waves can be inferred from that of the longer waves in normal reflection, well and good, but in my opinion a more direct method is preferable.

The essential point is this: Does the facsimile method supply any evidence which could not have been equally well supplied by the normal-pulse method? It is my firm conviction that it does. In the first place, there is the question of wavelengths. The facsimile method gives effective layer heights, etc., on the required wavelength, perhaps not with high accuracy; but in the absence of alternative methods the information is of great value. Secondly, it gives clear evidence of the normal mode of zigzag transmission between the earth and an effectively constant, fictitious, equivalent height, which could hardly be inferred with equal cogency from the results of vertical-pulse measurements. Indeed, Mr. Hollingworth still casts doubts on this mode of transmission in spite of the evidence. Thirdly, and what is essential from the point of view of long-distance transmission, it gives some information as to the relative and absolute reflection coefficients of glancing-incidence waves. I doubt whether any inference from the vertical-pulse measurement could have supplied either the remarkable evidence of high-angle attenuation in the F layer provided by the results shown in Fig. 5, or the relative effects of high-angle attenuation during magnetic storms, shown in Plate 2(4). The analysis of the signal measurements would have been difficult, if not impossible, without the aid of the facsimile results. Finally, the vast amount of measurable material ensures a comprehension of the *normal* features freed from accidental variations, which are such a constant characteristic of short-wave transmission. On the other hand, the vertical-pulse method is certainly more suitable for determining penetration frequencies and, consequently, maximum layer densities. However, when confronted with the facsimile material, it was impossible to refrain from attempting to analyse it as in the first section of the paper; and when due regard is paid to accuracy, to which reference is made in the paper, the results of such an analysis seem to me to be of considerable value, not only in themselves, but as an alternative to the vertical-pulse method.

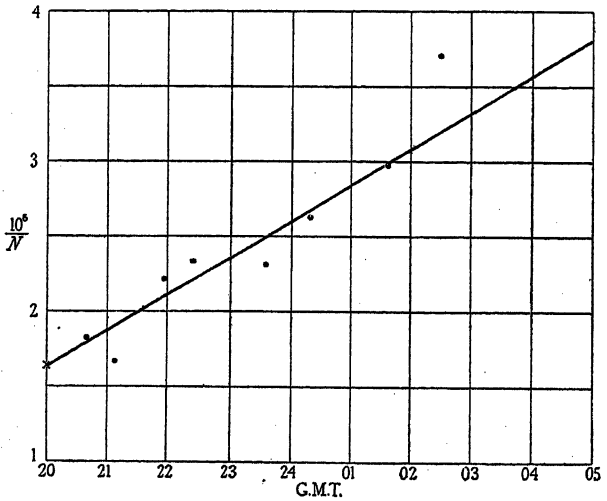


FIG. B.—New York test on 22·5 m (Oct. 1928).

NOTE.—Average deviation of points from straight line = 4 per cent.

Some further comment on the accuracy of what has been referred to as very unpromising material seems warranted. Taking two series of echo measurements at random from our material, I find that the probable error for a set of 13 measurements is 2 per cent, and for a set of 9 observations is 2·9 per cent. These values are typical. Again, the probable errors of the effective layer-height determinations from different ray angles are 3·2 and 4·6 per cent respectively. The systematic errors due to uncertainty as to the values of τ_0 and n are more serious, but such errors have been fully discussed in the paper and in extreme cases do not appear to amount to more than about 12 per cent, except with very glancing rays, the results for which were generally rejected. With regard to the accuracy of the determination of the night run of the densities, and, consequently, the recombination coefficient, Fig. B shows a typical curve of $1/N$ plotted against time. It is derived from measurements taken on the Somerton, N.Y., circuit in October 1928. There appears to be no systematic deviation from the linear relation, although individual values may differ by as much as 10 per cent, except the last, which is 16 per cent in error and is of little weight.

The accuracy is not such as would allow the deviation (if any) from the linear recombination law to be measured, and it is only sufficient to enable α to be determined within about 15 per cent. Reviewing the evidence, I think we may say that $7 \times 10^{-11} < \alpha < 10^{-10}$.

Considering Mr. Turner's comments in detail, he has, in effect, criticized the interpretation of the measurements on the ground that since the distribution of ionic density along the path is not uniform the ideal ray-geometry assumed may be considerably in error, and hence the deductions from this ideal may also suffer. It must be remembered, however, that the horizontal gradients of electronic density are on the average very small, so that any deviation from the ideal geometry, which assumes equally spaced hops and equal incident and reflection angles, is also very small. I have recently been able to calculate the ray paths in a layer which is graded both horizontally and vertically. The effect of such a horizontal gradient depends, of course, on the direction of the ray relative to the gradient. If the gradient is across the direction of the ray there is lateral bending, for which there is some evidence. If along the direction of the ray, the incident reflection angles are unequal and the length of the hops consequently varies along the path. I have calculated as an example the change in the angle of reflection for an extreme case. The horizontal gradient being derived from our calculated and empirical charts of the F-layer densities, with an angle of incidence of 60° (elevation 30°) the change in the angle of reflection is only 1·5°, i.e. 58·5° (elevation 31·5°). A little consideration will make it clear that an ideal ray of 59·25° incidence differs inappreciably from the actual ray. The doubt as to the behaviour of the first angle ray and as to its time of travel (τ_0) is to my mind the most serious objection, but the limits that can be set to τ_0 keep the resultant errors in N within fairly well-defined and not too large limits. This has been discussed in the paper itself, and the margin of error has been given. That attenuation and not lack of electrons may limit the reflection of high-angle rays, introduces an element of doubt into the calculation of maximum electronic densities, but this consideration is equally applicable to vertical-incidence pulse methods. The collateral evidence for deciding between these two alternatives is, I think, just as strong or even stronger in the case of the glancing-angle method (for example, the evidence in Fig. 5). It may be remarked that the lower curve in this figure cannot lie above the upper (as a matter of definition), so that the lower curve can hardly be a straight line.

I am inclined to agree with Prof. Chapman that, considering the very different technique, the general agreement between my results and those of Prof. Appleton, as far as I know them, is more remarkable than the minor differences, and this gives me confidence that the general lines of interpretation of the facsimile results are correct. A great deal more qualitative material might be cited to confirm the rather isolated numerical observations of a secular change in the Heaviside layer, which probably runs in parallel with the sunspot cycle. Such differences in the conditions of short-wave transmission are difficult to analyse definitely, but they give rise to a general conviction that the average density in the F layer has been gradually decreasing during the last three years, necessitating the use of longer waves, and that the attenuation in the E layer is also waning. The changes also appear to be more marked in high than in low magnetic latitudes, so that possibly the changes are associated with the extra ionizing agency discussed by Millington, who shows that it is mostly confined to the higher latitudes.

Mr. Hollingworth never did like "low angle" rays, hence, I presume, his preference for the rigidly defined "angle of incidence" of the physicists. I doubt whether this nomenclature is ever used in ballistics, and I consider the subject to be a kind of electromagnetic ballistics in which the angle of elevation is more appropriate. I am, however, quite open to conviction, but I hope that a better name will be found than "complement of the angle of incidence," which is pedantically correct for the "ray angle." Mr. Hollingworth exhibits a curve designed to illustrate how serious it is to neglect magneto-ionic effects even on the short-wave range. But the effect in the case under consideration is by no means so important as would appear from Fig. A, and for the very reason for which I am blamed, namely, because I use low-angle rays. The maximum angles of elevation involved are of the order of 30°, in which case μ lies between 0·8 and 0·9. Moreover, the frequencies used in the facsimile experiments are considerably higher than that for which the curve was calculated. For these reasons the only appropriate part of the curve is where $\mu > 0{\cdot}8$, say, where the difference between the curves is small. Also the spread between the two components represented by the two full lines is smaller, i.e. approximately half, for the case of the 22-m transmissions (13·6 megacycles instead of 6). For these reasons I do not consider the magneto-ionic effects to be of much importance in my experiments. This illustrates one of the advantages of the facsimile methods. The magneto-ionic corrections are practically negligible and only become of importance for normal incidence. I confess that I fail to understand Mr. Hollingworth's point about the high-angle long-hop rays. The maximum angle of elevation is practically the same for the long hop as for the multiple reflected ray. The fact that high-angle radiation of, say, 60° is observed does not necessarily imply that it has come by the long-hop path. In accordance with Fig. 11, a span of 2 500 km might be effected in five hops at an angle of 50° (elevation), provided the wavelength is long enough or the density great enough. The reflection coefficient is so high* that quite a large fraction of the energy may be carried along such a path. The Writtle–Somerton facsimile experiment shows that quite a large fraction of the energy is carried by a fourth-order ray at angles up to 87°, and it seems to me probable that the results obtained are due to a fifth- or sixth-order ray at 60° elevation.

Mr. Builder again emphasizes the difficulty of interpreting the facsimile results. This point has already been dealt with. I am inclined to agree with him as to the complexity of the patterns with normal-incidence rays, but the conclusions which I draw differ rather considerably from his. On reviewing the material from both sources, I am inclined to think that each method has its uses and also its drawbacks. The vertical-pulse method

* According to Appleton's results.

gives complex echo patterns, and the complexity, as far as I can see, is mainly due to magneto-ionic effects, which are inherent when vertical pulses on the longer waves are used, but it has the very great advantage of a rigid time reference supplied by the ground pulse. On the other hand, the facsimile echoes are, on the whole, more regular because shorter waves are used and lower angles of elevation, conditions which ensure that magneto-ionic effects are not important. The method suffers, however, from the grave defect of failing to supply a rigid reference time from which echo delays can be estimated. With regard to nomenclature, I merely followed Prof. Appleton's practice of denoting the lower and upper ionized regions by the labels E and F respectively. Mr. Builder appears to suggest a tentative alternative explanation of scattering based on observations of the multiple splitting of echoes, which is, no doubt, due to double-refraction magneto-ionic effects. Such multiple splitting, as he says, may give rise to blurred signals lasting as long as 3 milliseconds; hence, it is presumed, the scattering effects observed. But is this really an alternative explanation? Analysis of wave transmission in an ionized layer permeated by a constant magnetic field shows that, in any region where the change of μ in a wavelength of the radiation in the medium is small compared with unity, any single entrant ray is split up into two, and two only. Multiple splitting must occur in regions where this condition does not hold, where, indeed, there are rapid changes of μ. Multiple splitting implies just those scattering regions where μ changes rapidly, postulated in my theory. The scattering from such regions would occur even in the absence of a magnetic field, which, however, no doubt complicated the scattering process. The existence of multiple splitting seems to me to be merely another proof of the existence of scattering regions. The type of scattering or scattering regions associated with multiple splitting cannot be the only one, because multiple splitting increases in the winter months whilst the ordinary scattering is generally greatest in the summer. I think Mr. Builder has rather misunderstood my contention about the stratification of the F layer. Perhaps in his sense it would not be called stratified; that is to say, I do not contend that there are two definite maxima in the F layer, with a minimum between. It is only in the case of two maxima that a discontinuous jump from one layer to the other would occur, and Mr. Builder's evidence definitely rules out such a case. I merely wished to suggest that the F layer might be composite in the sense that it might be built up of two normal curves, a normal curve being defined as the ionizing distribution that would be produced by a monochromatic radiation in an exponential atmosphere. Such a distribution would account for the fact that the effective layer heights measured by the longer waves ($\lambda > 40$ m) cluster round a value of about 210 km in the daytime, while the shorter ones give values of the order of 300 km. In considering the diurnal run of the maximum layer densities, I think it is clear that the curve is not constant, that many irregularities change the contour from time to time, and that ionization may occur in the night hours; indeed, we have observed such cases in the South African transmissions. Nevertheless, I feel convinced that it is possible to pick out occasions, such as those exhibited in our analysis, in which a continuous reduction due to recombination is the predominant factor and from which a definite, if not very highly accurate, value of the recombination coefficient can be found.

THE FLASH-ARC IN HIGH-POWER VALVES.

By B. S. GOSSLING, M.A.

(Communication from the Staff of the Research Laboratories of the General Electric Co., Ltd., Wembley, England.)

(*Paper first received 15th February, and in final form 7th March, 1932; read before the* WIRELESS SECTION *6th April*, 1932.)

SUMMARY.

The "flash-arc" phenomenon, sometimes called the "Rocky Point effect," is the spontaneous and complete breakdown of the high insulation normally afforded by a good vacuum between metallic electrodes. The breakdown does not, in general, follow immediately upon the application of the voltage, but is preceded by an interval or "time-lag" of widely variable duration.

Part I of the paper gives a general experimental survey of the properties, including visible effects, of the flash-arcs obtained by the discharge of condensers (capacitances 0·0001 to 0·0016 μF) through inductances (3·1 to 40 μH) in series with the discharge tube and with a device for measuring the peak current. The latter is a quick-acting peak-voltmeter responding in a very small fraction of a micro-second to the voltage developed across a non-inductive resistor.

The completeness of the breakdown with the larger condensers is shown by the small damping of the oscillatory current. With the smallest condenser, however, the oscillation is very heavily damped.

The maximum amplitude of the oscillations is generally much less than the value to be expected from the charging voltage. It follows that energy is expended in building up the arc path, and it is shown that 1 to 3 watt-seconds will give an arc of high final conductivity, whereas 0·2 watt-second will not.

From the recorded values of condenser charge and current maximum a minimum estimate of the duration of the initial building-up stage is found to be 2×10^{-7} to 4×10^{-7} sec., which is in agreement with Snoddy's value of 5×10^{-7} sec. from observation in a rotating mirror. This is compared with the time of flight of positive ions, which approaches 10^{-7} sec.

The discharge is easily transferred from one electrode to another; e.g. in a triode valve the grid and filament both take their share of the current.

Residual gas in the tube only affects the flashing voltage indirectly. A considerable rise of gas pressure has no effect, but a subsequent clean-up of the gas on to the electrodes lowers the flashing voltage.

Autelectronic currents from edges formed by fracture of the cathode also have little effect on the discharge voltage.

When a flash-arc is artificially encouraged by pilot discharges across loose contacts it is found that the initial expenditure of energy is no longer demanded, and that the flashing voltage may be very low.

The chief and most general visible after-effect in valves which have flashed is that widespread tree-like markings appear on the grid and filament supports, demonstrating the great mobility of the arc. The fine wires in the active part of the grid are, however, never damaged.

Part II of the paper compares the incidence of flashing in operation at various installations. At Carnarvon, Daventry 5XX, and Motala, and at short-wave stations, it has seldom or never occurred; at Daventry 5GB (two circuits) and at Rugby GBR (two circuits) it occurred frequently in some circuits a few years ago, but is now rare. It is concluded that:—

(*a*) Direct paralleling of anodes is dangerous if it permits concentration in the flashing valve of currents exceeding 5 to 10 amperes.

(*b*) The smaller the high-frequency output condenser, the safer is the circuit.

(*c*) The larger the inductance between each valve and the high-tension supply, the safer is the circuit.

(*d*) Individual anode resistances are a good safeguard, but they cannot be used for valves above the 10-kW size.

(*e*) Resistances in the high-tension supply are useful.

When several valves are used, subdivision of the circuit by providing separate input chokes and output condensers gives marked improvement. Recent larger valves of the 100-kW size have been found to compare well with the earlier smaller valves, although the circuit conditions are necessarily less advantageous.

Some general comments on rectifier valves are made.

Part III of the paper describes and discusses the time-lag. Short time-lags of the order of a few minutes are sensitive to voltage, a 3 per cent increase of which decreases the lag in the ratio of 10 or more to 1. Two theories are given, the detachment of surface fragments by slow yielding and the resulting violent autelectronic emission from newly formed points, and the "Schrot-effect" variation of a pre-existing autelectronic emission.

The long time-lags observed at Rugby, which are not so sensitive to voltage, are analysed statistically, and are shown to have a regular, but not in general a simple, distribution up to 15 000 hours. It is found that there exist sub-groups of valves having different intrinsic tendency to flash, and also that the flashing tendency of all valves decreases the longer they are in operation.

When after flashing once a valve is replaced in operation for a "second life," no correlation between the lengths of the first and second lives is found.

Continuous operation, or even merely continuous heating of filaments in early life, is found to reduce the flashing tendency. Gas wandering, which is encouraged by intermittent operation, is therefore held to assist flashing, but continuous pumping is not considered likely to prevent it.

INTRODUCTION.

Although a very high degree of insulation between two metallic electrodes can normally be attained by exhausting the space between them by modern high-vacuum technique, it is, nevertheless, possible for this insulation to break down spontaneously and completely. This phenomenon is known by various names, such, for instance, as

the "Rocky Point effect," after an American wireless transmitting station, which is one of several at which it has been observed.

The name " flash-arc " used in the paper has been selected as giving expression to the two most prominent features of the phenomena, first, the extreme suddenness of the breakdown following an interval (here referred to as the " time-lag ") during which the insulation is good, and secondly, the fact that when the breakdown occurs the magnitude of the current passing between the electrodes is limited only by the ability of the power supply and external circuit generally to maintain a relatively small voltage between them, a property characteristic of arc-like discharges. Time-lags of several thousands of hours and currents of some thousands of amperes have been measured.

Provided the power supply is interrupted soon enough, as by the usual protective devices, the electrodes suffer no damage nor is the vacuum necessarily impaired, the insulation restores itself completely for the time being, and a valve which has suffered a flash-arc can be brought into operation again.*

Hence the principal practical problem associated with the flash-arc has been either to reduce the probability of its occurrence by increasing the time-lag, or to arrest its development. In either case the object is to reduce to negligible proportions the remaining transitory interruptions of regular operation.

The flash-arc is probably not an uncommon phenomenon in certain kinds of high-voltage vacuum apparatus, but, being so transient an effect and doing so little harm, it has not attracted much attention until the last few years. In valves made with envelopes consisting completely of glass it is seldom observed, at least until voltages of 100 kV or more are reached. The same is believed to be true of silica valves, but in both cases the available information is scanty, probably for the reasons just given.

R. W. Wood,† so long ago as 1897, described " a new form of cathode discharge," which he refers to as an arc. His detailed description agrees in a striking way with what is now known of the flash-arc. Millikan‡ used as the source of spectrum lines in his work on the extreme ultra-violet a discharge between electrodes of various materials in a high vacuum, which seems to have been a flash-arc of the kind with which we are here concerned. Experiments on the electrical breakdown of a vacuum under similar conditions have also been briefly described by Hayden.§ Extensive and ingenious investigations of the passage of very large currents up to 20 000 amperes between electrodes of tungsten and of copper in a high vacuum have been described in abstract by Hull and Burger‖ and by Snoddy,¶ giving results, where similar properties are concerned, identical with those which will be described here.

None of these authors describe the time-lag in the sense of our definition. Hansford and Faulkner refer to it, however, and the discussion of this property in the case of the " back-firing " of the mercury-vapour arc rectifier by Slepian and Ludwig* reveals a certain measure of similarity between that effect and the flash-arc.

It was, however, in connection with high-power valves where the envelope, except for the necessary insulating portions, was made of metal cooled by an external agency that flash-arcs became for a time a prominent source of trouble, the general nature of which was summarized by Hansford and Faulkner some five years ago. This phase is now past, but during the period when flash-arcs were occurring in operation with sufficient frequency, useful information about them, such as could hardly have been obtained by means of laboratory experiments alone, was collected in the way described in the later sections of this paper.

PART I.

GENERAL EXPERIMENTAL STUDY OF THE PROPERTIES OF THE FLASH-ARC.

(1) Visible Indications.

There is in general, though not always, something to be seen when a flash-arc occurs between two electrodes. The breakdown, however, is frequently transitory owing to spontaneous interruption, and in any case it is seldom allowed to persist. The transitory nature of the phenomenon, and the effect of the time-lag (particularly if the latter exceeds a few seconds), frequently result in the visible evidences being missed, because no one happens to be looking in the right direction at the right time. Indeed, some diligence in continuous watching is in general necessary if flash-arcs are to be visually observed. In some cases under conditions otherwise known to be unfavourable to complete breakdown, nothing at all is seen, despite adequate facilities for good observation, although currents of many amperes can be shown to have passed. These cases will be described later.

Proceeding to cases where something just visible occurs, what is seen consists of single or repeated flashes of fluorescence widely distributed over the surface of the glass work. This fluorescence is easily masked by external illumination or by the light from the filament.

The most characteristic sign of the flash-arc comes next in order. This is the appearance of one or more minute star-like scintillations on the surface of the cathode. These scintillations indicate a complete, even though transitory, breakdown. Over a wide range they differ simply in brilliance; the brighter ones may have an apparent diameter of a millimetre, but there is probably some magnification due to " irradiation " in the eye. A sideways view of these large scintillations usually reveals a shape as of a blunted cone with its apex on the cathode surface. If the surface carries any loosely-adherent or finely-divided material, this cone is extended by numerous fine bright lines like meteor trails, which must be due to incandescent particles because the brighter ones are sometimes seen to be reflected when they reach as far as the other electrode or the glass work.† The scintillations themselves are only faintly tinted with colour.

It is only very violent breakdowns that show any continuous bridging of the gap between the electrodes. The

* R. V. Hansford and H. Faulkner: *Journal I.E.E.*, 1927, vol. 65, p. 303.
† *Physical Review*, 1897, vol. 5, p. 1.
‡ *Ibid.*, 1918, vol. 12, p. 167.
§ *Journal of the American I.E.E.*, 1922, vol. 41, p. 852.
‖ *Physical Review*, 1928, vol. 31, p. 1121.
¶ *Ibid.*, 1931, vol. 37, p. 1678.

* *Electrical Engineering*, 1931, vol. 50, p. 793.
† W. D. Coolidge and I. Langmuir: *Review of Modern Physics*, 1930, vol. 2, p. 167; and R. W. Wood: *loc. cit.*

luminous bridge does not take the form of a thin well-defined spark, but has diffuse boundaries. In the strong light of a valve filament it appears quite pale.

Since very similar experimental arrangements will produce either the flash-arc or the autelectronic emission of a pure electron current from local sharpnesses on the cathode—this latter current is more of the nature of a regular leakage than a breakdown of insulation—the marked distinction between the visible indications in the two cases should be noted, especially since both have been described together by R. W. Wood and others, including the present author,* in publications dealing with the autelectronic current. Experimentally the two effects can now be readily distinguished because the autelectronic current persists if a resistance of about 1 megohm is connected close to the tube and in series with it, whereas the flash-arc is either suppressed entirely or considerably reduced.

In the autelectronic case the visible indications are confined to those consequent on the impact of the emitted electrons on the anode or the glass work, as follows:—

(*a*) Unless the surface of the anode has been heated to fusion shortly previously, small specks of various colours, due apparently to traces of foreign matter, can be seen scattered about the area of impact.

(*b*) With stronger currents there is local and intense heating of the anode.

(*c*) If the electron beam strikes the glass instead of the anode, the glass fluoresces continuously in characteristic well-defined elliptical patches which at grazing incidence may be elongated into streaks.

(*d*) If these patches are bright there may be general fluorescence as well, which can justly be ascribed to the impact of the secondary electrons emitted from the patches.

The visible indications are thus so clearly different in the two cases that they need never be confused.

The description of the visible after-effects of flashing in valves connected to a power supply capable of maintaining an arc will be postponed until the general nature of the flash-arc has been considered.

(2) Preliminary Experimental Survey.

Some of the earliest experiments on the flash-arc revealed or foreshadowed so much of what was later confirmed concerning its essential properties, that a brief description of what happened may serve as an introduction to our general survey.

The electrodes of the discharge tube consisted of a copper cylinder and a loop of stout molybdenum wire. The loop was inserted symmetrically in one end of the cylinder, and through the other end the space between the electrodes could be watched. The loop was connected to the high-tension terminal of a Haefely transformer by several feet of suspended conductor; the cylinder was connected by a shorter lead to earth—at first directly, and later through a non-inductive resistance across which a combination of rectifier valve and electrostatic voltmeter was connected as shown in Fig. 1. The insulation of the voltmeter was high enough to enable a transitory voltage across the resistance consequent on the passage of a current between the electrodes to be read as a permanent deflection, and its capacitance was low enough to reduce to a fraction of a microsecond the time required for charging it through the rectifier.

It was found at once that when scintillations of very moderate intensity were seen in the tube the transformer was well loaded. The visible indications of a breakdown are thus not very conspicuous.

On inserting a resistance of about 100 ohms (about 30 cm of nichrome wire 0·1 mm diameter) and the voltmeter as described, readings of from 1 000 up to 5 000 volts, the insulation limit of the rectifier, were readily obtained. The substitution of a copper wire of the same dimensions as the nichrome reduced these readings to about one-third. With a carbon lamp of 2 400 ohms resistance the voltmeter sparked over; for this some 20 000 volts would be necessary. The nichrome-wire resistor indicated currents of peak values ranging from 10 to 50 amperes and more, and the substituted copper wire showed that their rate of increase was such as to induce some hundreds of volts across a very small inductance. On examination of the circuit it was evident that such currents could only arise from the sudden discharge of the high-tension wiring.

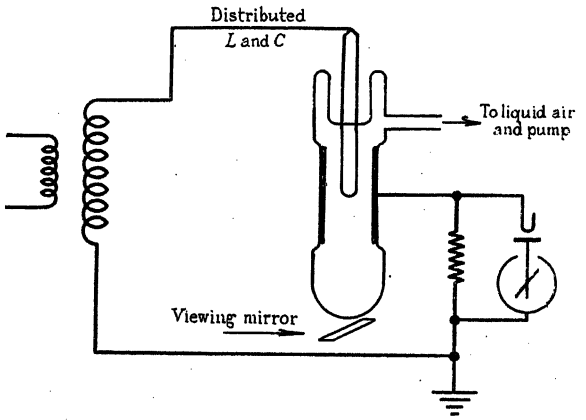


Fig. 1.—Experimental circuit (in its first form).

Further examination of the circuit showed that currents of even greater magnitude than those observed could be expected from the discharge of the wiring, given a sufficiently low resistance in the position of the discharge tube. The capacitance of the wiring was found to be a little over 100 $\mu\mu$F and its natural periods of oscillation—of which there were several—were of the order of 0·05 microsecond.

Now such a capacitance charged to 80 kV and discharging through a pure inductance with such a period would give an oscillatory current of 1 000 amperes maximum value, or 320 amperes if the discharge were rendered just aperiodic by the presence of a resistance of the critical value, 160 ohms.

The observed effects are thus consistent with the hypothesis of the discharge of the high-tension wiring through a high-conductivity path in the tube.

The magnitude of the currents observed reveals one more aspect of the discharge process. Since the initial charge in the wiring is not large enough to maintain such currents for more than a fraction of a microsecond, the

* *Philosophical Magazine*, 1926, vol. 1, p. 611.

duration of the growth of the current, or at least of the later stages of that growth, must be similarly brief. Thus the building-up of the high-conductivity path between the electrodes, or conversely the breakdown of the insulation of the space, must be an extremely rapid process.

(3) Constancy of High-Voltage Supply.

As is usual in experimental work on high-voltage breakdown phenomena, freedom from stray variations in the high-voltage supply used in experiments on the flash-arc is very necessary.

In the experiments described in the succeeding sections, the source of supply was a 30-kVA motor-alternator designed to be specially free from harmonics in the output wave-form. The supply to the d.c. driving motor and to the alternator field was Tirrill-regulated, with a normal range of voltage variation of 1 per cent. Actually, variations of as much as 1 per cent in the alternator voltage were seldom observed, sudden variations in the extraneous load on the d.c. supply being of rare occurrence during these experiments.

(4) Condenser Discharge Circuits.

The experimental study of the properties of the flash-arc consisted chiefly in the investigation of the effects occurring during the discharge of a condenser connected across the electrodes in the evacuated tube, the charging voltage of the condenser being increased until a spontaneous flash occurred.

The discharge tube was usually either of the simple form used in the preliminary experiments already described, or consisted of an actual valve of the 10- or 15-kW size used in the inactive state, i.e. with the filament unlit. Results obtained with inactive valves in this experimental circuit agreed with those given by valves in action in the appropriate oscillatory circuit, provided the voltage was applied for similar lengths of time.

As the preliminary experiment showed, a knowledge of the electrical properties of the condenser discharge-circuits is necessary. The constants of the three circuits used in the experiments to be described are given in Table 1.

The values given in the table do not, of course, completely specify the properties of the circuit. There remain the capacitance between the discharge electrodes (a few $\mu\mu$F) and the distributed capacitance of the leads.

Under rarely-occurring conditions, as will be described later, the discharge of the inter-electrode capacitance seems to have been sufficiently sudden to cause the propagation of a steep-fronted wave (*Wander-Welle*) along the leads.

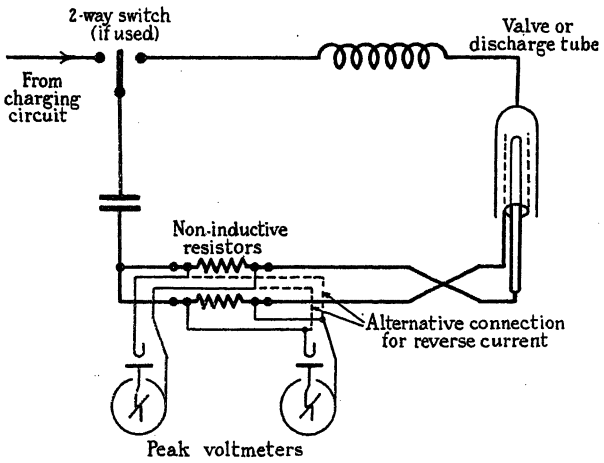


Fig. 2.—Condenser-discharge and current-measuring circuits.

The general arrangement of the circuit is shown in Fig. 2. When single discharges were desired, a 2-way switch was inserted at the junction of the condenser lead and the high-tension charging and discharging leads. The condenser was usually charged by means of a rectifier in series with the high-tension transformer, the rate of charging, or of recharging after a flash, being controlled either by liquid resistances of 1 to 10 megohms or by adjustment of the thermionic emission of the rectifier filament.

Alternatively, alternating voltages could be applied to the condenser, either at a frequency of 50 cycles per sec. from the transformer, or at high frequency (300 kilocycles per sec.) by making the condenser the capacitance of a self-oscillating circuit excited by a triode valve.

Table 1.

Condenser Discharge Circuits.

Condenser capacitance	Dielectric	Approximate inductance	Amperes per kV for undamped oscillation from $\sqrt{(C/L)}$	Critical resistance $2\sqrt{(L/C)}$	Period of oscillation
μF		μH		ohms	10^{-6} sec.
0·00010	Air	40 35 (coil) + 5 (leads)	1·55	1 280	0·40
0·00160	0·0015 μF of oil-paper cable	40 (as above)	6·2	320	1·74
0·00083	Air	3·1 (leads only)	16·7	120	0·32

(5) Current Measurements.

In a general study of the properties of the flash-arc, it is clearly important to have a ready means of making measurements of current under different conditions. The maximum value of the current, which varies

between wide limits, is of particular interest as a measure of the completeness of the breakdown.

The principal instrument used in the later experimental study of the properties of the flash-arc was developed from the combination of resistance and peak voltmeter used in connection with the early experiments. A high-speed cathode-ray oscillograph has been employed with success by Hull and Burger and by Snoddy for determining the relation between current and voltage during the very brief early stages. Their method of applying the voltage differs, however, from that used in the present experiments, in that they applied a very steeply-rising voltage wave, whereas in this investigation the flash-arc resulted from the maintenance of a steady applied voltage for an appreciable but spontaneously varying time. The fact that the deflection of the voltmeter gives a permanent record of the passage of a current is valuable, particularly since in some interesting

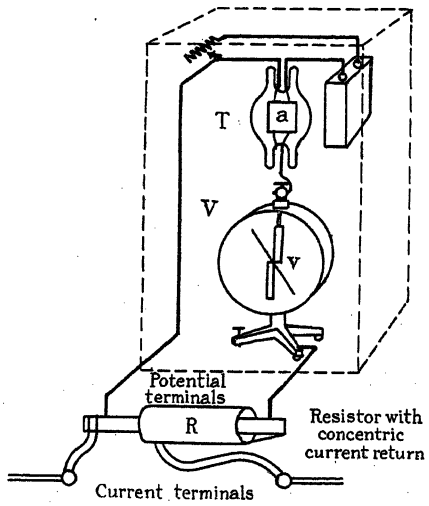


FIG. 3.—The peak-voltmeter and resistor for current measurements.

cases visible evidences of the breakdown were rarely present. The same property is also useful when the time-lag is being studied. The various components of the instrument in its final form are shown in Fig. 3.

The rectifier valve (T) is mounted directly on the insulated terminal of the Braun electrometer (V). The capacitance of the insulated system, consisting of the anode (a) of the valve and vane (v) of the electrometer, is thus kept low, and the single insulator reduces the chance of leakage. The lead connecting the anode and vane must be screened; otherwise, if there is any corona on the high-tension side of the circuit, charges accumulate slowly on the voltmeter.

If the whole instrument, with the exception of the two short leads to the resistor, is screened as shown in Fig. 3, one side of the screen being connected to the resistor, it can be used anywhere in the circuit. The screened instrument has worked well with the potential of the resistor fluctuating between that of earth and 40 kV above earth.

When, as in this case, a peak voltmeter is used without an auxiliary condenser in parallel with it, so that the capacitance between the electrodes of the rectifier valve is comparable with that between the voltmeter terminals, the final voltmeter reading is less, in a definite ratio, than the peak value of the impressed voltage.* This is due to the fact that the charge acquired by the voltmeter capacitance as a result of conduction through the rectifier has to be shared with the rectifier capacitance.

The rectifier used was of the simple thermionic diode type with a dull-emitting thoriated tungsten filament giving a saturated emission of 140 mA at the normal adjustment. The impedance of the rectifier was low, the voltage-drop needed to approach saturation of the 140-mA emission current being 100 volts.

Thus when the voltmeter capacitance was being charged through the rectifier the rate of charging was 2×10^{10} volts per sec., or 20 kV per microsecond, for an emission current of 140 mA and a voltmeter capacitance of 7 $\mu\mu$F. The voltmeter readings usually observed could therefore be obtained from pulses whose rise occupied well under one-tenth of a microsecond.

A minor limitation should, however, be mentioned; the full charging rate could be maintained only until the difference between the applied voltage and the voltage to which the voltmeter had become charged had fallen to about 100 volts, after which the rate of charging fell progressively as the current through the rectifier decreased owing to the diminution in the available voltage-drop. The response of the voltmeter to a single brief voltage pulse is therefore likely to be less than the actual maximum of the pulse by rather under 100 volts, and similarly, when it is not known whether the pulses are single or repeated, there will be an uncertainty of the same order in the estimation of the peak voltage. It was confirmed by direct experiment that these errors are seldom large enough to be of importance in the experiments to be described.

It was also found that the response to an air-spark discharge in the second circuit of Table 1 was unaffected when the charging rate was reduced to one-sixth of the normal value (by doubling the capacitance and reducing the emission to one-third); on further reducing the rate to one-tenth normal, one extra discharge was required. No errors due to lack of sufficient emission will therefore arise in the other circuits with quarter-periods of 0·1 and 0·075 microsecond.

A further experimental check on the response of the peak voltmeter was obtained by including in the discharge circuit two additional resistors each having a small sphere-gap (0·5-cm steel spheres) connected across it, the spheres being frequently polished with new emery paper.† One of the sphere-gaps was set to spark at a lower voltage than that recorded by the peak voltmeter, and this in the experiment did spark, whereas the other sphere-gap set for a voltage higher than that recorded by the peak voltmeter did not.

The insulation of the rectifiers was sufficient to withstand reverse voltages of 10 kV momentarily without breakdown, and of 5 kV continuously without excessively rapid leakage. There is a marked and immediate decrease in the leakage when the filament is switched off;

* C. C. PATERSON and N. CAMPBELL: *Philosophical Magazine*, 1919, vol. 37, p. 301.

† See O. BURAWOY: *Archiv für Elektrotechnik*, 1926, vol. 16, p. 201.

possibly the light from the filament produces a small photo-electric emission from the anode.

The design of the resistors across which the peak voltmeter is connected has clearly to be such that the effects of their inductance and skin resistance are negligible at the highest discharge frequencies encountered. The following three types of resistors were used. (*a*) Nichrome wires of diameter 0·1 mm and a few cm in length. (*b*) Short lengths of carbon-lamp filament mounted in an exhausted bulb and provided with separate current and potential terminals. (*c*) Glass tubes of length 10 cm or less and diameter about 1 cm, coated by the lustre process with a thin film of platinum of calculated thickness 3×10^{-6} to 6×10^{-6} cm.

The first two types were used only in the earlier experiments, and the nichrome wires only at discharge frequencies lower than 3×10^6 cycles per sec. The carbon filaments, though initially satisfactory, eventually gave trouble owing either to the contacts at the filament ends becoming erratic, or to deterioration of the vacuum giving rise to glow discharges which could not be assumed to have no appreciable shunting effect. The platinum-film resistors had resistances between 2·5 and 11 ohms, their ends were silver-plated, and the connections were made on the silver, the current connections being nearer the ends than the potential connections. The calculated inductance for a 10-cm length was only 0·045 μH, and the impedance at 3×10^6 cycles per sec. was well under 1 ohm. The effective inductance could be reduced to less than 0·01 μH for a 10-cm length by providing a concentric current-return sheath not included in the potential circuit.

The platinum film was immersed in oil for further cooling; nevertheless, it occasionally broke down, showing a narrow circumferential interruption of the film, if subjected to sustained discharge currents giving peak-voltmeter readings of 1 000 volts or more. This occurred more particularly if a train of air-sparks had been substituted for the flash-arc.

From the properties of the individual components which have been described, it may be inferred that such a combination of peak voltmeter and resistor should constitute a suitable instrument for its intended purpose of serving as a quick-acting peak ammeter. However, the performance of the combination was experimentally checked by using it in each of the three discharge circuits to measure high-frequency discharge currents the peak values of which could be calculated.

For this purpose a sphere-gap in air (2·5-cm diameter steel spheres) was inserted into the discharge circuit in substitution for the flash-arc tube. The ratio of the first current maximum to the discharge voltage should then have given the value in amperes per kilovolt shown in Table 1, less an appropriate small correction for the damping during the first quarter-cycle. From a study of the results it appeared that errors as great as 10 per cent in the absolute measurement of peak current are unlikely. This degree of accuracy is amply sufficient for the study of flash-arc currents, which can seldom be repeated at all closely.

In many experiments on the flash-arc, some of which, being of special interest, will be described later, the peak-voltmeter reading recorded by the flash-arc was reproduced, using a substituted air-spark. The flash-arc current was then taken to be equal to the calculated value of the air-spark current. By this substitution method, reliance on absolute measurements of current was in large measure evaded.

One point concerning current measurements remains to be mentioned. In no kind of current-measuring instrument should the ratio of peak current to discharge voltage exceed the characteristic value of the amperes per kilovolt if the discharge circuit is acting as a simple condenser-inductance combination. In the great majority of flash-arc discharges the recorded amperes per kilovolt did not exceed the value characteristic of the simple circuit. There were, however, three readily recognizable sets of conditions under which excessive readings were observed. These were a succession of violent discharges, the use of a flash-arc tube of relatively high inter-electrode capacitance, and the production of flash-arcs at unusually low voltages owing to pilot discharges at loose contacts between electrodes. As will be seen later, all these conditions are favourable to the building-up of the flash-arc with unusual rapidity, making possible the appearance of steep-fronted *Wander-Wellen* to which the resistors could no longer be expected to act as non-inductive resistances.

(6) Damping of Flash-Arc Condenser Discharge.

The effective resistance of the flash-arc built up by the discharge of the condenser of a given oscillatory circuit can be inferred from the damping of the oscillatory current. This can be observed in two ways. The first is by means of the ratio of the readings of two peak ammeters connected in opposite ways so as to record current maxima of opposite sense. Observations of this kind show that for the larger condensers (0·0016 and 0·00083 μF) the damping was always considerably less with the flash-arc than that measured in the same way with an air-spark current of the same amplitude. For the circuit used with the 0·00083-μF condenser the critical resistance which would first make the discharge aperiodic was 120 ohms. This gives a definite upper limit to the effective resistance of an oscillatory flash-arc in the circuit in question. Actually the resistance was much less than 120 ohms, for the observed ratios were close to unity, indicating a resistance much less than the critical value.

When the smaller (0·0001-μF) condenser was used the results obtained were totally different from those given by the larger. The second maximum was always very much smaller than the first, and sometimes too small to give a visible record, indicating very heavy dampings approximating to an aperiodic discharge, and this although the critical resistance for the circuit with the loading inductance was now high—rather over 1 000 ohms. With this condenser also, scintillations were very rarely seen.

For the flash-arc, therefore, where condensers of different sizes are concerned the factor determining whether the discharge will be aperiodic is not the critical resistance but the size of the condenser. The aperiodic discharge can hardly be called a breakdown, and it is probably in most practical cases innocuous.

These results illustrate the importance of external-circuit conditions.

The second method of estimating the effective resistance of the flash-arc gives information as to the damping during a longer period than that occupied by a single cycle. Two peak voltmeters were used, connected in the same direction across a single resistor. One of them was adjusted as usual so as to act as a peak ammeter recording the first maximum in the sense selected. The action of the other was made slower by reducing the emission of the rectifier filament. It follows, as illustrated in Fig. 4, that a train of smaller damping causes a larger deflection of the peak voltmeter, and a larger ratio of this deflection to that of the instrument which records the first maximum.

Using this method with single discharges in the circuit of the 0·0016-μF condenser, comparison with the

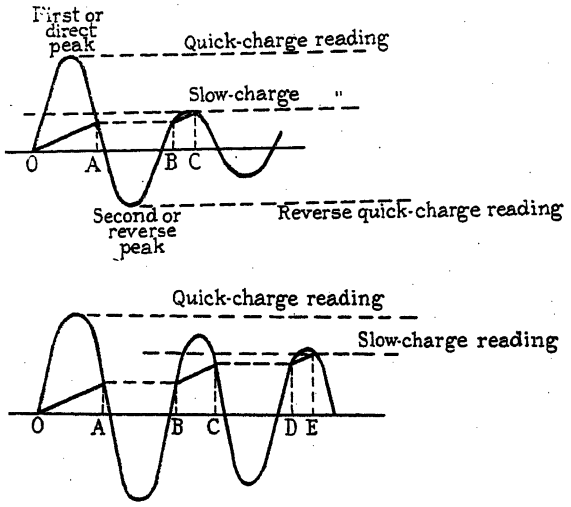


FIG. 4.—Action of a damped oscillation on a slow-acting peak-voltmeter.

equivalent air-spark showed that for the flash-arc the ratio of the reading of the slowly-charging instrument to the quickly-charging one was higher for the flash-arc (about 60 per cent) than for the air-spark (about 40 per cent) indicating that the flash-arc gave the lower damping, and that this low damping persisted at least until the amplitude of the oscillatory current had fallen to about one-half of its initial value.

(7) THE INITIAL EXPENDITURE OF ENERGY.

By a fortunate chance the constants of the condenser discharge-circuits were found to be such as to enable two features of the early stages of the breakdown to be clearly revealed by the measurements of peak currents, in spite of the inherent limitations of that method.

The first current maxima recorded for flash-arcs are found to be in general less than the air-spark value, and sometimes much less. Indeed, it is only when violent discharges of the larger condensers occur that equality is approached. Readings exceeding the air-spark value are, as already mentioned, very rarely observed. In making the comparison it was found to be more convenient to determine the charging voltage which in the air-spark case produced the same peak-voltmeter deflection as the flash-arc. In one series of comparative experiments the flash-arc currents observed in a number of discharges at 55 to 65 kV between a molybdenum cathode and a copper anode ranged between 20 and 40 per cent of the equivalent air-spark currents, although from the small damping of the subsequent oscillations they might have been expected to be at least as large if not actually greater.

These results show that the growth of the current, i.e. the initial stage of the breakdown, follows a different course in the flash-arc case.

The low value of the current at the first current maximum implies that the kinetic energy of the oscillation at this point ($\frac{1}{2}LI_1^2$) is far less than the original potential energy ($\frac{1}{2}CE_0^2$) of the charged condenser. The difference ($\frac{1}{2}CE_0^2 - \frac{1}{2}LI_1^2$) represents energy dissipated in building up the conducting path. In the case quoted, this dissipation was between 96 and 84 per cent of the initial energy. During the initial stages the discharge path thus has a high but progressively decreasing resistance.

The small damping of the subsequent oscillation shows that in this case the final breakdown was always effectively complete, and since the initial energy was about 3 watt-seconds we know the energy (rather less than 3 watt-seconds, or 0·75 calorie) which is needed to carry the breakdown through its initial stages. Similar experiments on the aperiodic discharge obtained when the smallest condenser was used with the same electrodes, showed that the initial energy then available (0·2 watt-second or 0·05 calorie) was definitely insufficient to complete the breakdown.

This necessary initial dissipation is a somewhat variable quantity, even with a given pair of electrodes: it probably depends to some extent on the condition of their surfaces. Changing the actual material of an electrode can produce a still more marked effect. With a nickel cathode instead of the molybdenum cathode referred to above, the amplitude of the oscillation corresponded to a smaller initial dissipation of little more than 1 watt-second (0·25 calorie), and similarly with the small condenser the discharge—though very heavily damped—was definitely not quite aperiodic.

(8) DURATION OF INITIAL STAGES OF BREAKDOWN.

The constants of the condenser discharge circuits also happened to be suitable for providing some indication of the duration of the initial stages of the breakdown. Consideration of the available initial charge in the condenser and the magnitude of the first maximum of current shows that, brief though these stages are, they must have more than a certain minimum duration.

In the early stages when the energy of the condenser is being dissipated in the tube, the growth of the current is controlled by the effective resistance of the conducting path, which is initially high. In the final stages the growth is controlled by the inductance of the circuit, and the potential energy of the condenser is in process of conversion into the kinetic energy of the current in the inductance. The two stages no doubt overlap, but it would seem that the duration of the conversion stage

cannot differ much from one-quarter of the natural oscillation period of the circuit. From the experimental data we can determine hypothetical time-intervals E_0C/I_{max} based on the extreme supposition that the condenser of capacitance C charged to voltage E_0 is discharged by a constant current which has always the value I_{max} observed for the first current maximum.

In the cases of the aperiodic discharge of the smaller condenser, where the conversion stage is unimportant, the minimum time E_0C/I_{max} was found to be 2×10^{-7} sec. for the heaviest currents observed. For these currents the breakdown was not of course completed within this time, which corresponds to about one-half a normal oscillatory cycle. If, again, for the oscillatory discharges of the larger condenser, which always represented a complete breakdown, we deduct from E_0C/I_{max} one-quarter of the normal period (6×10^{-7} sec.) to allow for the conversion stage, we have about 4×10^{-7} sec. left for the initial stage for the smaller observed values of I_{max}/E_0. This method of estimating the minimum duration of the initial stage thus leads to a definite result in these cases, although the extreme assumption of the constant discharge current certainly means that the duration is considerably underestimated. Even a linear growth of the current would double these times, and, further, since the positive ions necessary for the high conductivity are themselves produced by the passage of the current, we should expect this to grow at an increasing rate in the early stages. The times obtained by these rough calculations agree with the figure (5×10^{-7} sec.) obtained by Snoddy from direct observation in a rotating mirror.

A possible physical meaning for this minimum duration of the initial building-up stage of the conducting path is disclosed by considering the time of flight of a positive ion between anode and cathode under the conditions of the experiment. For any but the lightest positive ions, the time of flight is found to approach 10^{-7} sec. Hence a process requiring the successive passage of several relays of positive ions would account for the observed minimum duration, and since, as we have seen, this minimum is probably considerably underestimated, a considerable number of such relays is likely to be necessary.

(9) The Sharing of the Flash-Arc Discharge Between the Grid and Filament of a Triode.

Since the main power supply to a valve in operation is connected to the filament and anode, it was clearly important to find out to what extent the filament system, which is more or less surrounded by the grid system, takes part in the discharge. A large number of experiments on this point have been made using various types of valves.

For this purpose the return lead from the valve to the condenser on the low-tension side was divided into two similar leads in parallel (Fig. 2) which could be connected to the grid and filament respectively. Each lead had its own resistor and peak voltmeter so that the relative magnitudes of the discharge currents passing by way of the grid and of the filament could be observed.

It was found that both peak voltmeters invariably gave readings; with some valves the current set up in the one circuit was consistently the larger, with others the larger current was produced in the other. In a few cases the currents were roughly equal.

Before attempting to infer from these results what takes place inside the valve, we have to find an answer to two questions relating to the external circuit conditions. There is first the simple question whether the passage of the discharge current along one of the leads of the divided circuit would produce a reading of the peak voltmeter in the other. The answer to this is definite: an air-spark between grid and anode external to the valve produced a 1 000-volt deflection in the grid-circuit voltmeter and nothing visible, i.e. nothing as great as 100 volts, in the filament-circuit voltmeter. The second question is a double one. If a low-resistance discharge passes inside the valve between one electrode —the grid, for instance—and the anode, there will be a redistribution of the potential throughout the discharge circuit. This will not apply to the branch leading to the filament, because no current flows there. What potential difference will arise between grid and filament, and will it be big enough to excite a new discharge between them? Calculation from the ratio of the inductance of the grid lead to the total inductance, and experimental observation by means of an auxiliary sphere-gap between grid and filament, both gave the result that the voltage-drop in the grid lead amounts to about 20 per cent of the total.

Direct experiment showed that the discharge voltage between grid and filament amounted to about 50 per cent of that between grid and anode, even with an appreciable time-lag. Hence it is to be concluded that the potential difference between grid and filament arising from the discharge between grid and anode could not in this circuit have excited a second instantaneous discharge between grid and filament.

What happens in the valve, therefore, must be some sort of division of the original discharge between the two low-potential electrodes, whichever of them was responsible for initiating the discharge. Here the temporary potential difference between grid and filament which has been discussed may play a part in diverting some portion of the discharge current at an early stage from the electrode initially responsible to the idle electrode. Similarly, for valves in actual operation there may be a disadvantage in the use of a protecting resistance in the grid lead which is not effective in suppressing the discharge; this disadvantage is that the voltage-drop in such a resistance constitutes a potential between grid and filament which helps to divert the arc, and might, if very high, excite a new instantaneous discharge.

(10) The Flashing Voltage.

In many kinds of high-voltage breakdown the term "breakdown voltage" has no definite meaning unless stipulations are made as to the duration of the application of the voltage. This is particularly true of the flash-arc, since it shows such marked time-lag effects.

These time-lags will be discussed in more detail in later sections; for present purposes the "flashing voltage" may be defined, in accordance with actual experimental procedure, as the voltage which will produce a flash within a few seconds after application.

Experiment has shown that it is impossible to give a simple answer to the question: What are the factors which determine the flashing voltage? However, as will shortly be shown, the residual gas in the space between the electrodes has no direct influence on the flashing voltage. It must therefore be concluded that the determining factors are located on the boundaries of the space; so that the flashing voltage must depend not only on the shape, disposition, and material, of the electrodes, but also on the intimate details of their surface condition. The control of surface condition is at present more a matter of intelligent empirical routine than of actual knowledge of the mechanisms concerned.

(11) Effects of Residual Gas on the Flashing Voltage.

Some typical experiments on the evolution and clean-up of gas in relation to the discharge voltage will be described. Three valves were used. The results were in many respects similar in all three cases. The valves were first tested in the experimental circuit and the flashing voltages for time-lags of a few seconds noted. These exhibited a steady rise in the course of a not very large number of flashes, as shown in the first column of Table 2. After this the state of the vacuum was observed (Table 2, second column) in the ordinary static test circuit with the filament lit at normal brilliancy and the anode voltage and dissipation raised where possible to the standard value. The amount of gas found to have been evolved and the extent of the subsequent clean-up varied. On returning to the experimental circuit, however, it was found that in all these cases the flashing voltage had fallen again almost to its original value, rising as before in the course of a few flashes.

Comparing these results with those of a similar experiment in which the clean-up was performed in an auxiliary valve attached to a side tube, it was found that whereas in both cases the flashing voltage rose during the evolution of gas, its value subsequent to the clean-up was unchanged when the clean-up was in the side tube, but relapsed nearly to its original value when the clean-up was in the valve itself.

It is clear from these experiments that the presence of free gas does not lower the flashing voltage, but rather the reverse. That the liberation of gas was not the cause of the progressive rise of the flashing voltage is shown by the persistence of the final high voltage after the clean-up in the side tube. Further, the same kind of rise was generally observed when the discharge tube was connected with a pump to remove the gas as it was evolved.

Hence the gas evolution was a result of the repeated flashing, but it was an important result, for the subsequent restoration of the gas by clean-up on to the surfaces on which it was presumably originally condensed resulted in the relapse of the flashing voltage.

The fact that in the second case quoted in Table 2 the relapse was quite marked for a small clean-up, is particularly interesting. Although there is some doubt as to the meaning of a static gas test as a quantitative measure of the pressure of free gas when the test is carried out as here, with some thousands of volts of anode potential, it is not improbable that the small clean-up referred to corresponded to a pressure change of less than 10^{-6} mm. Hence the quantity of gas which can produce a relapse by its clean-up may be very small indeed.

Table 2.

Flashing Voltage, and Evolution and Clean-Up of Gas.

Specimen valve	First test			Static gas test	Second test		
	Flashing voltage		Number of flashes		Flashing voltage		Number of flashes
	Initial	Final			Initial	Final	
	kV	kV			kV	kV	
A	9·5	15	15	Very soft, slow clean-up	12·5	25	27
B	22	25	29	Hard, small clean-up	16	23	16
C	25	33	26	Soft, good clean-up	25	30	3

The influence of gas-wanderings of the kind here described on the behaviour of valves in intermittent operation, will be discussed further in Section (24).

(12) Effects of a Superposed Autelectronic Emission.

In many experiments, and more particularly in those in which the discharge tube was in such a state that rather high voltages had to be applied in order to obtain flash-arcs, visible signs of the presence of autelectronic or " cold cathode "currents were evident at voltages well below the flashing voltage.

In one case a careful study was made of the effects on the flashing voltage of the appearance of steady autelectronic currents superposed in this way on the flash-arc. The experimental tube in this case had as cathode a square-headed loop of tungsten wire 1 mm in diameter, mounted facing a copper disc which constituted the anode. After a number of determinations of the flashing voltage had been made, the cathode wire was broken at one of the square bends by the application of an external force through the flexible platinum thimble on which the wire was mounted. In consequence of this, autelectronic effects, of which very little had been seen

before, became prominent, as was to be expected from the gross disturbance of the form of the cathode surface by the sharp edges formed at the point of fracture. These evidences became definitely visible when the autelectronic current was about 10 microamperes, and this condition was reached when the applied voltage was about 20 per cent less than the flashing voltage. By using the peak-voltmeter resistor as the shunt for a suitable galvanometer protected by high-frequency choking coils, the autelectronic current was in some cases observed up to the moment of flashing, when its value amounted to a few hundred microamperes.

At the voltages in use, 40 to 50 kV, autelectronic currents of this magnitude would be sufficient to produce strong heating of the anode if they were maintained; they would also produce X-rays, which might possibly influence the behaviour of the tube.

The flashing voltage, however, proved to have been little affected by the breaking of the filament. Its spontaneous variations had been studied before the breaking, and after the breaking its average value was rather less than before, but was within the range of variation previously observed.

If, therefore, these superposed autelectronic currents had any effect, its magnitude was small—less, for instance, than that of the " cleaned-up " gas referred to in Table 2.

Thus, although the existence of an autelectronic current may be a necessary condition for the earliest initial stages of the flash-arc, it is not of itself a sufficient condition in the case of flash-arcs such as those with which we are here concerned, which occur some little time after the voltage has been applied and the autelectronic emission established. If such flash-arcs do originate in an autelectronic emission, it would seem that this does not partake of the normal steady form.

(13) Flash-Arcs Due to Loose Contacts and Pilot Discharges.

We have seen that in the normal process of developing a flash-arc there are initial stages during which a considerable amount of energy is consumed in building up the highly conducting arc-path which is characteristic of the later stages. It is experimentally possible to dispense with the initial stages, or, more exactly, to substitute something else which leads to the same final results.

The occurrence of flashes in consequence of a variable contact between the cathode and an otherwise insulated support has been briefly described by Hansford* and also by Slepian† in the case of mercury-arc rectifiers. A similar opportunity for studying in the experimental circuit the effect of a loose tungsten-to-tungsten contact was provided by a C.A.T.6 valve returned from Daventry 5GB on account of persistent flashing. In this valve the filament springing was defective, so that the filament loops could become distorted until they made contact with the grid.

When a high-frequency voltage was applied to the electrodes, the filament being cold, this valve behaved normally—even when tapped with a rod—as long as the filament and grid were both on the low-tension side, whether they were connected together or each was provided with its own low-tension lead. When, however, the voltage was applied between filament and grid with the peak voltmeters connected opposite ways, there was first a small discharge at a very low voltage (less than 5 kV) and then a short-circuit. When the valve was tapped to break the short-circuit the peak voltmeters both gave very large over-readings, and scintillations deep down in the valve were seen by reflection. On disconnecting the grid completely and applying the high-frequency voltage to the anode—so that there would be an induced potential difference between grid and filament as long as there was no contact, or alternatively any contact would have to carry the grid-anode capacitance current—flashes were obtained spontaneously at low voltages of the order of 1 kV between anode and filament. The induced voltage between grid and filament must, of course, have been lower still.

The fact that flashes were obtained at such abnormally low voltages indicates a great reduction in the initial consumption of energy under the special conditions of the experiment, for the total energy of the condenser at maximum charge for these voltages was much less than the usual initial consumption, and thus the normal building-up process could not have been completed owing to the lack of available energy. In addition, the abnormally high readings of the peak voltmeters showed that the current pulse had so steep a wave-front that the resistors were no longer effectively non-inductive; this, again, could only happen if the arc was built up much more quickly than usual. We have therefore to suppose that in this case a local pilot-arc across the imperfect contact acted as an initial source of conducting material for the main arc-path from the anode, just as we suspected that a previous violent discharge might have done in some otherwise ordinary cases.

There is also evidence* that local discharges across insulating surfaces, whether occasioned by the dissipation of conducting films or otherwise, are attended by similar results. Deliberately introduced variable contacts and also the inferred breakdown of *insulating* films on extensive *metallic* surfaces are cited by Slepian† as causes of " back-firing," i.e. breakdown in the non-conducting phase, in the case of mercury-arc rectifiers.

(14) Visible After-Effects of Flashing.

Certain visible after-effects of a high-power flash will now be described. Although the discharge current in the valve represents a short-circuit or heavy overload on a power supply of 100 kW or more, the general absence of serious effect on the valve is in agreement with the experimental fact that the resistance of the discharge path in the valve can be quite low, so that the short-circuit power tends to be dissipated elsewhere in the circuit and not in the valve.

Visible changes of the electrode surfaces are, however, usually produced, although the valve may not be seriously harmed. In the triode type of valve, tree-like white markings appear on the supports of grid and filament systems, particularly the latter. Under the

* *Journal I.E.E.*, 1927, vol. 65, p. 813.
† *Electrical Engineering* (*Journal of the American I.E.E.*), 1931, vol. 50, p. 793.

* H. G. Hughes: *Journal I.E.E.*, 1927, vol. 65, p. 817. † *Loc. cit.*

microscope the surface oxide is seen to have been removed and fused into globules along the edges of the markings; sometimes the clean metallic surface thus exposed is also fused into globules. Melting of massive iron parts and alloying with molybdenum are sometimes seen, apparently owing to the striking of maintained low-voltage arcs between the leads in the filament circuit.

The extent of the tree-like markings indicates a wide-spread wandering of the discharge over the supports. The movement of the ions in the magnetic field produced by currents of many amperes would account for this. Such mobility in the discharge is important, since it implies that a weak discharge from the grid (which has usually series resistances in its external connections) might be transferred to the filament, and so to the main power circuit. This transference has been studied experimentally, as already described.

If the discharge current passes through two limbs of the filament placed side by side, these are often pulled together by the magnetic attraction of the parallel currents, causing a short-circuit and spoiling the valve. The other two limbs may show no distortion whatever. That so violent a distortion should occur in the fraction of a second before the high-tension circuit breakers operate is a proof that the discharge current is very large compared with the normal filament heating current.

Visible markings are produced on the anode, but these are too vague for significance, with one exception, which will shortly be described.

No effect on the grid mesh has, as yet, been observed. The grid wires are fine and should melt relatively easily. The fact that they do not melt suggests that the central active portion of the valve does not take part in the arc. In this part of a cooled-anode valve more than in any other, the state of the electrode surfaces approximates to that of the electrode surfaces of a glass valve, in which flashes would not be expected.

In the exceptional case of a loose contact situated in the central active portion of the valve, flash-arcs localized in the same region are, of course, to be expected. In one particular instance of this a water-cooled copper anode 3 mm thick was perforated by melting opposite to a loose contact between a bowed filament and the grid of the valve.

In rectifier valves the visible evidences after flashing are different from those observed in triodes, but differences are to be expected because the functions of the electrodes are transposed. The voltage applied between the electrodes of rectifiers is high enough to produce flashing only when the filament is positive with respect to the surrounding copper electrode. It is found that the filaments of rectifiers which have been subjected to violent flashing in this reverse direction sometimes show pitting of their surfaces due to local fusion, the pits being in the central (full-temperature) part of the filament. The copper opposite the pits shows zones and lines of disturbance of the surface deposits which, consisting mainly of evaporated tungsten from the filament, are usually found in this region of the valve. No tree-like markings are produced elsewhere, so that nothing is likely to be seen on looking into the valve.

PART II.

THE FLASH-ARC IN PRACTICAL OPERATION.

(15) General.

The operation of similar valves in different kinds of installations has shown that the tendency to produce flash-arcs varies considerably with the circuit conditions. This section describes the behaviour in this respect of a number of representative installations, and seeks to interpret it in terms of what direct experiment has revealed about the flash-arc. It is to be remarked that whereas in the experiments the time-lag was deliberately reduced for convenience to the order of seconds, the time-lags for flash-arcs in operation must necessarily be much longer, hours at the least and preferably hundreds or thousands of hours. Nevertheless, nothing is observed which belies the supposition that once the flash-arc has started it follows the same course, whatever the time-lag has been. Section (24) deals with the duration of these longer time-lags.

In what follows here, there is no intention of criticizing the design of the respective installations, which were regarded as new ventures at the time when the observations were made. Similarly, as regards the valves, the cases quoted are not representative of present-day performance, which is now generally satisfactory, if not everywhere and always perfect.

The circuits considered are the later power amplifier stages of the following installations:—

(*a*) A telegraph transmitter of high power at Carnarvon, and a telegraph transmitter of higher power at Rugby.

(*b*) Broadcast transmitters of medium power modulated by anode voltage in the last stage (Daventry 5XX and Motala).

(*c*) Two versions of the Daventry 5GB medium-power experimental broadcast transmitter with low-power modulation.

Some general comments will be made on flash-arcs occurring in rectifier valves used for the high-tension supply in similar installations.

The differences between the various circuits from the flash-arc point of view must lie in their response to an incipient flash-arc in one of the valves. The following is a tentative description of the supposed course of events. We have seen from the experiments, and it is no doubt generally known, that a short-circuit between the valve electrodes in the form of a low-resistance arc can be very rapidly built up by the discharge of a condenser through the valve. In the operating circuit, therefore, what we suppose to happen first is the discharge of the capacitance of the valve and its immediate connections. Transfer of the arc, e.g. from grid to filament, probably occurs even as early as this stage. It is quickly followed by the discharge of any condensers in relatively non-inductive connection with the valve. Concurrently, there is a concentration in the flashing valve of the whole supply current to the bank of parallel valves. Then follows a growth of the current through the high-frequency chokes, more or less delayed according to their inductances. This leads to the discharge of the condensers of the smoothing system. Finally, there comes the actual short-circuiting of the power supply and the operation of its protective devices.

If at any stage in this sequence of events the arc current falls to a low enough value for a long enough time, the arc will go out and the breakdown will be harmlessly arrested. Such abortive breakdowns have been demonstrated by inserting a resistor and peak voltmeter or similar quick-acting indicator in the anode lead.

The following method of suppressing one of the minor stages so as to enforce a delay in the train of events may be suggested as an example of a favourable circuit condition. In the simple circuit shown in Fig. 5, the anode stopping condenser (or high-frequency output condenser) C has a certain approximately steady charge. When the oscillatory condenser B has its maximum charge, as shown, the voltage between the valve electrodes is a maximum and there is therefore the greatest probability of a flash-arc. The short-circuit in the valve joins C and B in parallel, and their charges—being of opposite sign—tend to neutralize, performing a damped oscillation of relatively high frequency. In general, there will be a residue representing the excess of the one charge over the other, and this, being shared between C

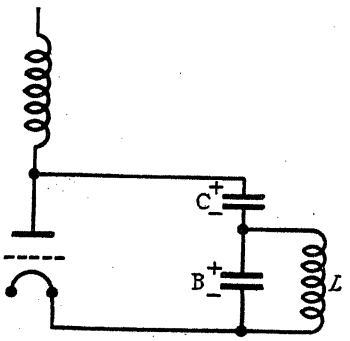


FIG. 5.—Suppression of the flash-arc in the high-frequency stage.

and B in parallel, subsequently dissipates itself through L in a second damped oscillation of lower frequency. This oscillation will be of long duration, since it will be out of resonance with the output circuits and therefore undamped by them. It keeps the arc active while the extra current in the high-frequency choke is being built up.

In the particular case when the charges in C and B are equal, however, the first or higher-frequency oscillation will neutralize them completely, and the circuit will be reduced to premature quiescence. The greater the resistance of the connections between C, B, and the valve, the more quickly will this change take place. If now the value of the current through the high-frequency choke, which may not as yet much exceed its steady value, is not enough to maintain the arc, it will go out and the breakdown will have been arrested.

Thus there might be an advantage in so proportioning the voltages and capacitances of the anode stopping condenser and the oscillatory condenser that their charges are equal when the latter is charged to the maximum.

(16) CARNARVON.

The installation at Carnarvon comprises a long-wave telegraph transmitter with twelve C.A.T.1 valves in the last stage of the high-frequency amplifier, working with an input of some 80 kW at 9 000 volts supplied by a d.c. generator. This transmitter has been working for $5\frac{1}{2}$ years, and of the 90 valves which have been in use, only one has given flash-arcs, and that during the tuning-up of the station. The tip of the central support of the filament system was melted by the arc; the significance of this was not realized at the time.

The course of variation of the voltage between the valve electrodes is simple. A high-frequency voltage of probable amplitude about 2 000 volts is applied to the grid. In consequence an intermittent current is produced in the anode circuit, and this builds up in the main oscillatory circuit a high-frequency current which induces in the anode circuit a large high-frequency voltage superposed on the 9 000-volt d.c. supply voltage. This voltage is out of phase with that in the grid circuit, and in consequence the voltage between anode and grid

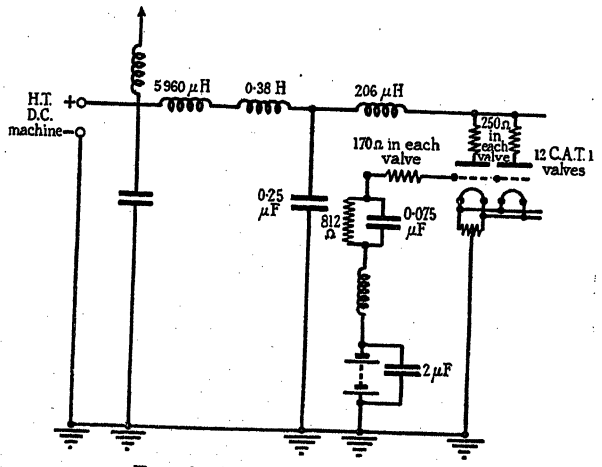


FIG. 6.—The Carnarvon circuit.

fluctuates at high frequency between a low value and a value at least twice the anode supply voltage, i.e. at least 18 000 volts. The maximum may be 10 per cent or so greater than this, because there is in effect a d.c. voltage of at least 1 000 volts in the grid circuit also. As this is negative to the filament, it has to be added to the anode supply voltage before doubling.

During the spacing periods of the telegraphic signals the voltages are much reduced.

The parts of the circuit in immediate connection with the valve are shown in Fig. 6. The insertion of a resistance (fairly non-inductive) of 250 ohms in series with the anode connection of each individual valve merits particular notice, as this arrangement was for a long time peculiar to this station. It was adopted by Round as a general protection against parasitic self-oscillations and valve defects in the early days of the development of high-power valves, and it has proved very effective in suppressing flash-arcs, as will be seen later by comparison with other stations. The overall efficiency is, however, definitely reduced thereby, perhaps to the extent of doubling the effective anode losses by the use of resistances of so high a value. This restricts the use of such a method of protection to valves of this size, since with larger valves, each taking a high

current, the losses in the resistances would become prohibitive.

(17) Daventry 5XX and Motala (Sweden).

The Daventry 5XX and Motala installations consist of two very similar broadcast transmitters in which the anode supply of 9 000 to 10 000 volts (provided by rectifiers) to the last stage is modulated by means of a "speech transformer." Daventry 5XX has four C.A.T.1 valves in this stage with all their electrodes directly connected in parallel, taking an input of 40 kW, and Motala has five C.A.T.5 valves with a total input of 50 kW. At Daventry 5XX only two valves out of the first 30 gave serious flash-arcs. In both, the tip of the central support was partly melted. In addition, however, there has been evidence of transitory arcs, particularly in later years since the range of modulation has been somewhat increased. Further, some breakdowns of insulation have occurred in the speech transformer, a circuit component across which high voltages might be expected to appear as a result of discharges. At Motala no trouble has been reported, although, as regards flash-arcs, C.A.T.5 valves have not behaved well elsewhere.

The circuit diagram of this type of transmitter is shown in Fig. 7. There are no individual anode resistances, and a further point of difference from the simple tele-

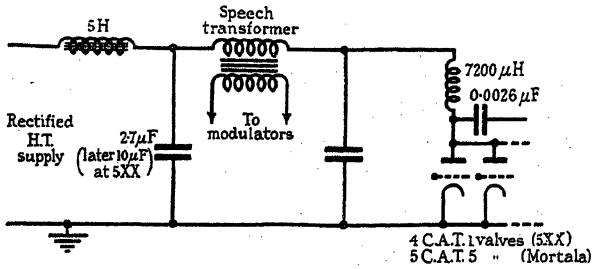


Fig. 7.—The Daventry 5XX circuit.

graphic installations previously described consists in the inclusion of the speech transformer for impressing the low-frequency modulation on the high-tension supply to the anodes. The range of this modulation varies continually according to the type of speech or music transmitted, but it is not supposed to exceed a swing between zero and twice the potential of the mean high-voltage supply, 10 000 volts.

This implies, as previously explained, the application of high-frequency voltages between grid and anode of peak value about twice the maximum supply voltage, i.e. about 40 000 volts. This constitutes a very severe condition and it is somewhat surprising that the valves used have withstood it so well. However, the duration of this voltage is necessarily brief, and the time-lag associated with the flashing phenomenon may well help to prevent its occurrence. The range of modulation was formerly rather less (by between 10 and 20 per cent) and this may be the reason why flash-arcs have only latterly been observed.

The inductance of the speech transformer is very high, and it is most probably this that protects the valves by delaying the discharge of the smoothing condenser. In addition to this, but probably of less importance, is the limitation of the current from the power supply imposed by saturation in the rectifier valves. This limitation should, however, reduce the damage in a valve which does build up an arc. Although this circuit imposes severe conditions, their ill effects tend to be mitigated by the properties inherent in it.

The installations so far described provide examples of circuit arrangements which do not encourage the development of flash-arcs. Although these have occurred, they have rarely if ever been a serious trouble. To these installations may be added the short-wave beam stations in which the capacitances directly connected to the valve are only of the order of the inter-electrode capacitances. In these stations the high-tension current is taken through a choke of several millihenries and is conveyed to each valve through a resistance of several hundred ohms. During five or six years of operation, in which period some hundreds of

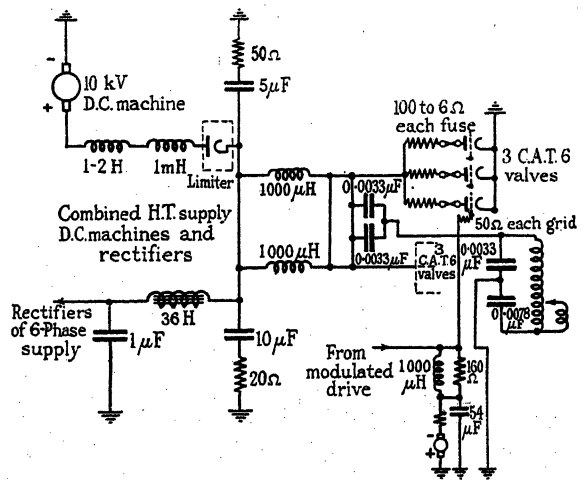


Fig. 8.—The Daventry 5GB circuit (first version).

valves have been employed, no flash-arcs have been proved to occur in these installations.

The other installations now to be considered, Daventry 5GB and Rugby GBR, each provide a comparison between a favourable and an unfavourable circuit.

(18) Daventry 5GB (First Version).

The first version of Daventry 5GB was an experimental broadcast transmitter of the kind in which the modulation is impressed in one of the low-power stages. The last amplifying stage had at first six C.A.T.6 valves connected in parallel as shown in Fig. 8, with an input of about 90 kW at 10 000 volts from a combination of a d.c. generator and valve rectifier operated in parallel. Later the circuit was modified by "subdivision," as shown in Fig. 9.

This station in its original form provided the first case of serious trouble from flash-arcs, in spite of the fact that (as will be explained) the voltage conditions were much less severe than in the 5XX type of circuit.

Early specimens of the C.A.T.6 type of valve flashed frequently, even when the anode voltage was lowered to 8 000 volts (later 9 000) in order to keep down the number of interruptions.

The connection to the anode of each valve consisted,

at least at first, of about 5 inches of light fuse wire. The fusing of this by the discharge located the valve responsible, and probably reduced the softening, since in most cases the valve was replaced without being "cleaned-up."

Later valves behaved very much better than the original ones, giving few instead of frequent discharges, although they were started at 9 000 instead of 8 000 volts.

The circuit diagram is shown in Fig. 8. The high-frequency voltage is already modulated when applied to the grids. The high-frequency output of the valves is thus modulated accordingly, but the high-tension supply voltage remains constant. At full modulation, therefore, the valves fluctuate between something approaching a static condition and the full high-frequency excitation corresponding to the supply voltage. The maximum high-frequency peak voltage between grid and anode should therefore be about twice the supply voltage, i.e. about 18 000 volts. The voltage conditions are

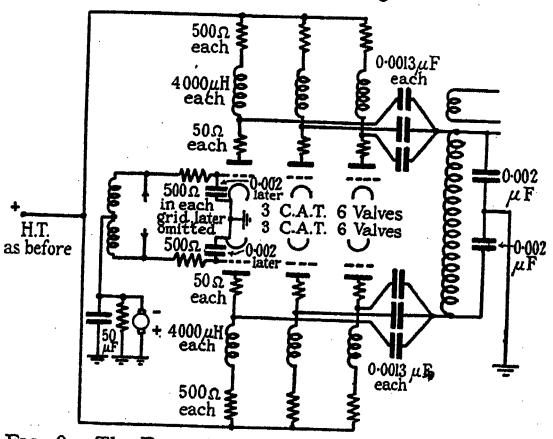


FIG. 9.—The Daventry 5GB circuit (second version).

much the same as in a telegraphic circuit, although the loading is different since the average efficiency is low.

In searching for the source of the trouble encountered with this system, it is important to note in the first place that the direct paralleling of the valve anodes permits a rapid concentration of the total high-tension supply current in any valve that begins to flash. This current is, in this case, about 9 amperes. Whether this is or is not quite sufficient in itself to ensure the growth and persistence of a fully-developed arc is not certain. As we shall see later, a somewhat larger current did maintain a permanent arc.

Individual anode resistances of various values (100 ohms at first, but later much less) were used, but these did not result in any certain improvement. Since the mean anode current per valve was from 1·2 to 1·7 amperes, it was probably impossible to make them high enough.

The next point to be noted is the possibility of discharging the 0·0066-μF high-frequency output condensers through the valve and the 0·0033-μF tapping capacitance of the main oscillatory circuit. This discharge circuit has very little inductance indeed.

Referring again to the circuit diagram (Fig. 8), it will be seen that the inductance of the high-frequency chokes interposed between the anodes and the high-tension supply is unusually small, only 500 μH. This is understood to be essential if the modulation of the load is not to affect the constancy of the supply voltage. From the present point of view, however, it is a disadvantage, because first the charge in the large 15-μF smoothing condenser, and after that the unlimited current of the d.c. machine, are much more quickly available for building up the low-resistance discharge path in the valve. This view is confirmed by the improvement resulting from the increase in this inductance when the circuit was changed to the second form.

After 2 months' working with the C.A.T.6 valves, a C.A.R.2 valve was inserted in the lead from the d.c. machine as a current limiter, the filament being adjusted to a saturation current not much in excess of the normal working current supplied by the machine. This prevented the opening of the machine circuit-breakers, but resulted in a permanent arc forming across the anode-fuse terminals when the fuse blew. The current in this arc would be some 15 amperes, and a corresponding sustained discharge in the valve is almost certainly implied. This is the more interesting as no special harm seems to have been done to the valves.

(19) DAVENTRY 5GB (SECOND VERSION).

During the last month of operation with the original circuit, some 70 discharges were recorded, coming in bursts with quiescent intervals of about a week at a time. After the circuit had been changed there were—leaving out of account one abnormal valve—only 7 discharges in 3 months' operation, about 900 hours, and all these discharges occurred in the middle of the second month. Four valves, of which one had a very bad record, were used in both circuits, and of those used in the new circuit the majority were of the original set, which were potentially bad. It is therefore very unlikely that the improvement was in the valves.

There were several cases of grid-filament contact among the valves used in the new circuit, and it is possible that without these the few flashes observed might not have happened.

The improvement thus demonstrated at the time of the actual change-over was subsequently confirmed when no flashes were reported in a year's working at 11 400 volts, and this in spite of the removal of the 500-ohm resistances from the anode circuits. Further confirmation of the rarity of the flash-arc in the new "subdivided" circuit has since been obtained from the transmitters of the B.B.C. regional scheme and other similar installations elsewhere.

Referring to the circuit diagram (Fig. 9), various changes from the former circuit (Fig. 8) will be seen. The division of the valves into two banks on the "push-pull" principle is probably only relevant to the present question in so far as it may permit the use of higher protecting resistances with a given degree of distortion due to their presence. The chief other differences are, first, that the valves are no longer directly paralleled and therefore the concentration of the high-tension supply current in a single flashing valve at an early stage in the flashing is no longer possible. Secondly, the high-frequency output condenser has been subdivided so that each valve now has its own unit of one-sixth the former value. This

reduction may be important since the energy of the charge in this condenser is still very quickly available for building up the low-resistance arc, the low-inductance discharge path through the main oscillatory condenser being retained.

The high-frequency choke has been similarly subdivided, making it possible to increase the inductance in series with any single flash-arc to 8 times its former very low value. The growth of the arc current is therefore correspondingly delayed.

Further, there is the addition of high protecting resistances of 500 ohms placed behind the high-frequency choke and therefore coming into action only in the later stages of the breakdown scheme, since they carry only the d.c. component of the anode current. In this position they produce no more distortion than a much smaller resistance placed close to the valve. Individual

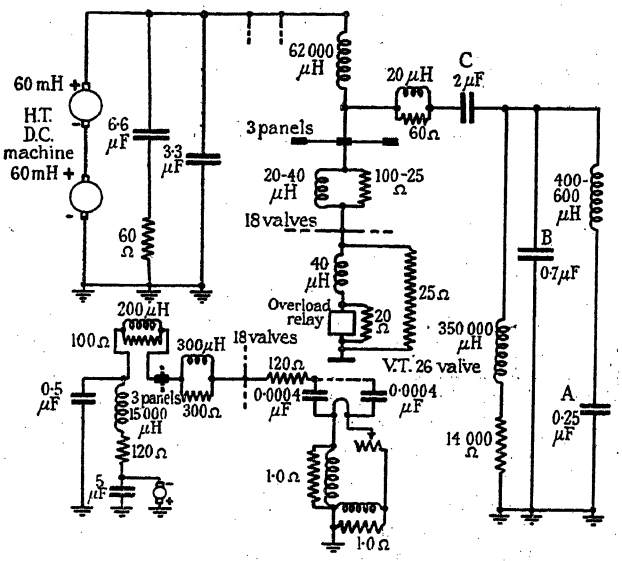


FIG. 10.—The Rugby GBR circuit (main panel).

anode resistances of 50 ohms next to the valve were temporarily restored, although it has latterly been more usual in similar installations to have an inductance of a few microhenrys in parallel with them, which makes them ineffective as regards the flash-arc current.

It is to be remarked that the protection obtained by applying this principle of individual d.c. supply and high-frequency output is more effective the lower the power of each valve unit and the greater the number of units; conversely, a single high-power valve with an equal tendency to flash would be a disadvantage compared with a number of low-power valves connected in this way. This argument has, however, latterly lost some of its weight, since the experience of the past year has shown that higher-power valves have definitely less tendency to flash than the low-power ones had at the time we have been considering.

(20) RUGBY GBR.

The Rugby GBR station consists of a telegraph transmitter of very high power employing in the last amplifying stage, or main panel (Fig. 10), 54 valves with an input of nearly 500 kW at the relatively low voltage of 5 500 to 7 000 volts supplied by a d.c. generator. The preceding stage has three valves supplied from the same source. The comparison between the two stages is interesting for our present purpose because, although flash-arcs were frequent at first in the main panel, they were non-existent when similar valves were employed in the intermediate panel.

The valves with whose behaviour we are here concerned (of a type known as V.T.26) were very similar to their predecessors and contemporaries, the C.A.T.1 valves at Carnarvon and Daventry 5XX. They had all been oscillated more than once for half an hour with an 18-kW input at 12 000 volts, and most of them had also been oscillated at 15 000 volts with a 200-ohm anode resistance. In consequence of these tests no trouble from flashing at lower voltages was expected.

In operation, however, flash-arcs were frequent in the main panel; the times of their occurrence in this first batch of valves are given in Section (24) as an example of the distribution of time-lag. It was indeed only the residue after the elimination of a considerable

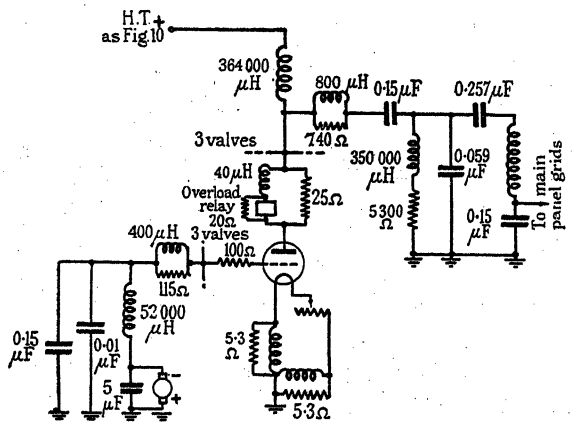


FIG. 11.—The Rugby GBR circuit (intermediate panel).

proportion that gave satisfactory operation. With 54 valves in operation at once, satisfactory operation—as now attained—means that flashing must be a rare occurrence.

The circuit diagram for the main panels, of which there are three of 18 valves each, is shown in Fig. 10. The circuit for the preceding intermediate panel of three valves is given in Fig. 11. In the main panels there is nothing that is likely to be effective as a protecting resistance. The individual grid resistance of 120 ohms is barely large enough, and, as will be seen later, the main discharge does not take place in the grid circuit. The resistances on the anode side are intended for the suppression of short-wave oscillations, and are ineffective for the present purpose because they are shunted by inductances of relatively small value.

The direct consequences of its size distinguish this circuit from those so far considered; everything is on a very large scale. The total high-tension current has a value of some 70 amperes, which according to the experiments corresponds to a fully-developed arc of low resistance. Since the whole of this current will con-

centrate rapidly in any valve which has begun to flash, the full development of any incipient flash in this circuit seems almost certain. Further, there is to be considered the discharge of the condensers associated with the valve; this will, in this case, proceed concurrently with the concentration of the high-tension current. Here we have to note the great size (2 μF) of the high-frequency output condenser C, which is always charged to a d.c. potential equal to that of the high-tension supply (6 500 volts), and secondly that the tapping to the main oscillatory circuit is not connected to the inductance but to a large condenser B (0·7 to 1·05 μF), the other side of which is directly earthed. The energy available in this condenser system is very considerable, and, although not so large as that in the smoothing condenser of the first Daventry 5GB circuit (Fig. 8), it is more quickly available for building up a low-resistance discharge path in the valve because the total inductance in the circuit is so small, apparently not more than 100 μH as against the 500 μH at Daventry 5GB (first version).

For the further maintenance of the arc after the initial sharing of the charges of condensers C and B there will be (as already described in connection with a similar circuit), the succeeding stage, very long-drawn-out in this case owing to the low natural frequency of the circuit, namely the dissipation through the 400- to 600-μH inductance of the residual charge in C and B and also the original charge in A. By the time all this is over, the increase in the current through the high-frequency choke, starting at the rate (E/L) of some 10^5 amperes per sec., will have gone far enough to ensure the handing-on of the short-circuit to the smoothing condensers and the low-inductance d.c. generator.

To sum up, in each stage of the whole train of events the conditions are such as to encourage the growth and maintenance of any incipient flash, but the concentration of the supply current arising very early and persisting throughout might very possibly be sufficient in itself to cause a flash-arc.

The conditions in the intermediate panel (Fig. 11) are more favourable to the valves. The total supply current is only 4 or 5 amperes, the condensers have less than one-tenth the capacitance, and in addition there is inserted between the valves and the high-frequency output condenser a fair-sized inductance (800 μH) shunted by a resistance of 740 ohms. Thus, without taking into account the lower voltage, the conditions are probably better than at Daventry. This is borne out by the fact that none of five valves used in this circuit have flashed, although they are even earlier specimens than those in the main panel and have run for many thousands of hours.

As regards the parts played by the grid and filament in the discharge, certain tentative conclusions can be drawn from what has been observed in the main panels at Rugby. In the first place, the violent distortion of the filaments in some cases and the markings on the filament supports in others, show that the main discharge passed that way. Further, each valve on the panel has an overload relay placed next the valve and operated by the anode current. This relay operates the main high-tension circuit breakers for the whole installation. The grids of the valves are connected by way of their individual 120-ohm resistances with a common grid busbar. In consequence, if the discharge in any one valve took the form of a short-circuit between grid and anode it would be expected that the potential of this busbar would be raised to a sufficiently high positive value to increase the anode current of all the valves to the saturation figure (about 6 amperes). This current would operate the anode relays of all valves. Now it is seldom or never found that more than one anode relay is operated by a discharge; hence the discharge does not act in such a way as to keep the grid positive to the filament for any appreciable time.

In single-valve test circuits, however, where grid leaks of higher resistance were used, it was found that with a simple grid leak (even of as low a value as 3 000 ohms) and no sensitive anode relay, the first effect of a discharge was a violent bombardment of the grid. That this was due to a reversal of the action of the grid leak initiated by a discharge between grid and anode, was confirmed by the fact that the same effect was produced by momentary connection of the grid (through a 2 000-ohm resistance) with the anode outside the valve. It is known, of course, that given a sufficiently high-resistance grid leak the grid can be maintained at a positive potential owing to the secondary emission from the grid providing a reversal of the grid current. This effect showed that the initial discharge did often take place between grid and anode.

When a battery was connected across one half of the 3 000-ohm leak so that the potential across this half could not reverse, the effect disappeared both with internal discharges and with external short-circuits. The former condition is dangerous because the violent bombardment, in which the grid lights up very brightly, softens the valve. In general, whenever there is any likelihood of flashing, grid leaks of high value should not be used unless shunted by batteries.

So far then, it seems that both grid and filament can take part in a discharge, but that in operation the nature of the external circuit affects the result.

(21) Flashing Under Operating Conditions—Summary for Triodes.

The results of this comparative study of the incidence of flashing in various installations will now be summarized.

If the use of valves of the 10- to 15-kW size had been confined to stations such as Carnarvon, Daventry 5XX, the short-wave beam stations, and the later broadcasting stations similar to the second version of Daventry 5GB, flashing might not have been regarded as an important matter. It was the early history of the first version of Daventry 5GB and of Rugby GBR that brought the flashing problem into prominence, and gave warning that all was not well with the quality of the valves and that there was an element of danger in the expansion of installations to larger and larger sizes.

As regards the circuit arrangements, comparison of the results obtained in the various installations considered has brought out the following points:—

(*a*) Direct paralleling of anodes seems to be dangerous if it permits immediate concentration in the flashing valve of currents exceeding a minimum value, which probably lies between 5 and 10 amperes.

(*b*) The smaller the high-frequency output condenser, and—

(*c*) The larger the inductance included between each valve and the high-tension supply, the safer the circuit.

(*d*) Individual anode resistances constitute a good safeguard, but it is apparently only in valves of the C.A.T.1 or 10-kW size that they can be made high enough to be effective, and even then the consequent loss of efficiency is not desirable.

(*e*) Resistances in the high-tension supply are useful.

(*f*) The larger the valve, the more difficult it becomes to obtain protection by suitably arranging the circuit; it is therefore essential that large valves should be made as perfect as possible in themselves, independently of circuit conditions.

As regards the valves, the progressive improvement in later years at Rugby, where operating conditions have remained unchanged, shows that immunity from flashing is not only possible but has in large measure been achieved even under difficult conditions.

It was without doubt fortunate that the warning came when it did, because if it had been postponed until larger valves had come into use, opportunities of obtaining operating results would have been fewer and the number of valves used would have been too small to provide reliable statistical data such as are discussed in Section (24). As it is, the results so far obtained for large valves of approximately 100 kW compare well with the later results for the smaller valves, although the circuit conditions cannot be so favourable and although the valves have been operated at higher anode voltages.

(22) Rectifier Valves.

Comment on flash-arcs in rectifier valves is necessarily more speculative than in the case of triodes, because there have been no cases of persistent trouble capable of yielding definite statistics for comparing the behaviour of similar valves in different circuits.

When a rectifier valve is in use the voltage across it is only high if the valve is non-conducting and the filament positive to the anode. This reverse voltage has a maximum value which is usually about twice the d.c. output voltage of the installation.

The intermittent short-circuiting of the highly inductive transformer circuits by flash-arcs in rectifiers has no counterpart in circuits in which triodes are ordinarily used. It gives rise to surges having very high voltage maxima, which are revealed by sparking over the glass between filament and anode, and must often exceed 100 000 volts; they have also caused trouble by producing flash-overs elsewhere. Ample clearances are therefore desirable.

Since several rectifiers are usually associated with a polyphase transformer combination, surges due to one valve may set up flashing in others which are in themselves reliable. The valve initially responsible is not, therefore, always readily located, and flashing in rectifiers is troublesome out of proportion to the frequency of its occurrence, which with most types of rectifiers is happily not great. Relays indicating reverse currents have been found useful in this connection.

The arc current in the flashing valve must, after static charges in the associated capacitances have been disposed of, pass through the conducting companion valve or valves in the opposite phase, and will be limited by the thermionic emission of these valves if they do not immediately flash in the conducting direction. Hence it would seem to be better to distribute valves among a larger number of phases, rather than to increase the current in each of a smaller number.

No explanation is forthcoming for the fact that while the occurrence of flashing in 2-phase, 4-phase, and various 6-phase circuits is quite obvious, in 3-phase circuits it is apparently not so. Valves failing in 3-phase circuits are described simply as "soft," and no interruptions or difficulty in locating defective valves have been reported.

PART III.

THE TIME-LAG OF THE FLASH-ARC.*

(23) Short Time-Lags.

The fact that the flash is in general preceded by a quiescent interval or time-lag is an important characteristic of the flash-arc. The available data relative to the time-lag are divided between two ranges, (*a*) short time-lags of a few seconds or minutes, and (*b*) long time-lags of tens, hundreds, or thousands of hours. This section deals with the short time-lags of range (*a*).

Many experiments have been made with the object of studying the complex variations of the voltage required to produce a flash after a short time-lag. An early suspicion that there might be some connection between the length of the time-lag and the applied voltage led to the adoption of time schedules for raising the voltage by fixed steps of a few per cent at regular intervals until a flash or flashes occurred. One result of this procedure has been to show that, so far as short time-lags are concerned, there are many other factors which influence the flashing voltage to a much wider extent than variation of the time of application. Experimental determinations of the relation between time-lag and voltage are therefore not easily obtained, particularly since some at least of these other factors are likely to vary spontaneously with time to such an extent that the results can hardly be trusted for time-lags as long as an hour or so. In the absence of sufficient knowledge and control of these other factors, indications as to the nature of the voltage/time-lag relation can only be obtained in those cases in which there is actual evidence that these factors were for the moment constant, or at least sufficiently so for the voltage to be the determining factor. We shall quote two such cases.

In both instances the cathode consisted of a loop of wire 2 mm in diameter suspended in an unbombarded copper cylinder connected to the pump. In the first case the wire was of molybdenum, but the surface deposits left after wire-drawing—consisting of a mixture of finely-divided metal, oxide and graphite—had been deliberately retained as a means of obtaining a long, regular succession of flashes. In the second case, which gave a similar result, the cathode was of clean nickel,

* Hull and Burger have used this term "time-lag" in a different sense, namely, to denote the duration of the transition from the pure electron discharge to the arc, i.e. what we have called the "initial stages of the flash-arc."

and this also exhibited regular flashing. In both cases the condenser which discharged through the flash-arc was a small one (about 100 $\mu\mu$F) and the inductance of the discharge circuit was some 40 μH. In these circumstances the oscillatory discharge was very heavily damped, being limited almost to a single pulse of current. The condenser was recharged relatively slowly, and surge over-voltages from the transformer were prevented in the first case by inserting between discharge condenser and rectifier, first, a liquid resistance of 8·5 megohms, then a condenser to earth of 0·0015 μF, and finally a further resistance of 1 megohm. In the second case the filament of the rectifier was simply dulled until its emission was reduced to a few milliamperes.

In the first experiment, that with the uncleaned molybdenum cathode, the discharge voltage was raised from 19 kV in steps decreasing from 10 per cent to 5 per cent at intervals of roughly 5 minutes until 42·5 kV was reached, at which point the voltage was held steady for 33 minutes. In this period 20 flashes were recorded. On lowering the discharge voltage to 27 kV no flashes occurred in a period of 2 hours. Reducing the voltage to two-thirds of the value for a time-lag of 1½ to 3 minutes produced a large increase in the duration of the lag. After these preliminaries were over the voltage was raised again in steps of 4 per cent until 46 kV was reached. Resuming next day at 46 kV, further flashes at this and higher voltages up to 54 kV were obtained (see Fig. 12).

The first step shown (46 to 47·5 kV) produced a flash in 1 minute after a previous quiescence of 5 minutes, and the last (52·5 to 54 kV) a flash in a few seconds after 10 minutes' quiescence. Granted the connection between voltage and time-lag thus demonstrated, the progressive increase of time-lag while the voltage was steady can be taken as expressing in another way the diminishing influence of the factors responsible for the initial low value of the flashing voltage. This diminution can, of course, be inferred directly in this experiment from the progressive increase in the voltage necessary to produce flashing with a given short time-lag.

In the second case (nickel cathode) a state of higher constancy was reached in which flashes occurred at fairly regular intervals of 1½ minutes over a period of 47 minutes at 61·5 kV. After this the voltage was lowered and then raised again rapidly to 63·2 kV, i.e. a value higher by nearly 3 per cent, and a flash occurred at once. On again lowering and raising to the previous value (61·5 kV) the next flash came after a distinctly longer lag, and, on repeating, after a longer lag still.

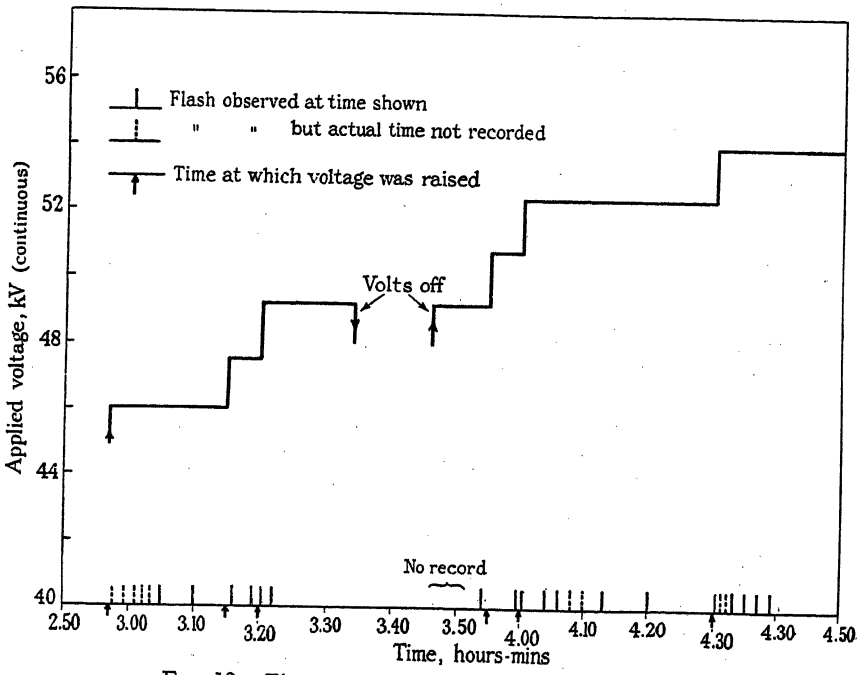


FIG. 12.—Time-lag and raising of applied voltage.

These results exemplify the general rule arrived at from numerous similar but less completely recorded experiments, that, other factors being constant, a reduction of 3 per cent in the voltage results in an increase of time-lag from values of the order of seconds to values of the order of minutes. The ratio of increase may be as low as 10 : 1, but it is hardly likely to be less. This is one of the properties of the flash-arc which have to be explained by any theory of its initiation.

Two such theories which have been tentatively considered will now be briefly stated. Both have as their basis the assumption that the first stage of the flash is an autelectronic or "field" emission of electrons from some small area of the cathode where the conditions are locally favourable. Snoddy's recent oscillographic determinations of the agreement of the initial current/voltage relation with the autelectronic law

$$I \propto e^{-1/V} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

now lend support to this assumption.

The first theory supposes the flash to be due to a sudden autelectronic current arising from points formed by some kind of surface rupture under the influence of the applied field. This idea is attractive because such mechanical yielding requires time. The relation between time and stress has been determined for the fracture of single crystal wires by Goucher* and by Schoenborn.† Both find that the time t and stress s are connected by an exponential relation $t \propto e^{s}$. Goucher's results show that with the specimen at 1 000° K. a 10 per cent increase of stress multiplies the time-lag by about 50. Schoenborn finds the time-lag to be multiplied by about 10 (presumably at room temperature) by a 10 per cent increase of stress. However, since a field as high as 10^8 volts per cm is required to give a surface stress of 5 kg per mm^2 (3·5 tons per sq. in.) and tensile strengths vary from 0·5 kg per mm^2 for soft metals up to 50 to 140 kg per mm^2 for strong metals, it is clear that, when the general surface field is of the usual order 3×10^5 volts per cm and the general stress only 5×10^{-5} kg per mm^2, mechanical rupture demands both local enhancement of the field and local weakening of the material. A sharp projecting fragment having a small area of attachment, or which did not adhere strongly, would satisfy both of these conditions. The formation of new points by the rupture would result in further enhancement of the field and sudden heavy autelectronic currents such as might, other conditions being favourable, initiate a flash-arc. This theory is consistent with the commonly observed progressive rise of flashing voltage by "fatigue," as illustrated for the first time-lag experiment in Fig. 12, and is applicable to cathode surfaces which have a structure less compact than a solid metal, as exemplified by the uncleaned molybdenum of the first experiment, or by rusty iron surfaces such as have given repeated discharges with displays of meteor-like trails. We should, however, expect fatigue to be permanent, whereas it is not always so, and the case of the solid metal surface still remains.

The second theory supposes that what is required to initiate a flash when other necessary conditions are favourable, is an autelectronic current above a certain critical value. It is not, however, necessary to suppose that this current has to be maintained for more than a very short time. Our conclusions as to the duration of the initial stages of the flash suggest that a fraction of a microsecond might be enough. If now an autelectronic current is present and is subject to spontaneous fluctuations distributed in amplitude and time in a manner analogous to the Schrot effect for thermionic emission, then the lower the voltage the lower will be the average current and the greater must be the ratio of the momentary enhancement required to reach the critical value of current to the mean fluctuation. Now the greater this ratio the less is the probability of its occurrence in a given time, i.e. the greater the average time-lag. A rough numerical test shows that an increase of time-lag in the ratio 10 : 1 might in this way quite well be associated with a decrease of 3 per cent in voltage.

Against this theory it can be argued that the presence of an autelectronic current does not apparently have a marked effect on the tendency to flash. However, autelectronic emission is a very local effect, and other necessary conditions may not be present in the limited area of its impact on the anode. If, therefore, we are content to regard the preliminary autelectronic current as a necessary condition of the flash, but not as a sufficient condition, the Schrot effect is a possible explanation of the time-lag.

Neither of these two theories is consistent with all the facts, but such consistency is not really necessary, since the factors known to influence the flashing tendency are so numerous as to point to the possibility of more than one way of initiating the flash.

In the experiments of Hull and Burger and of Snoddy the voltage was not applied continuously but in the form of an impulse the shape of whose rising wave-front was known. The "time-lag," in our sense of the term, has no meaning under such conditions. It would seem, indeed, that if the voltage wave rose continuously to a sufficient height, no effect of this kind could occur.

The use of voltage impulses of varying duration and amplitude suggests itself as a suitable method of investigating very short time-lags.

(24) Long Time-Lags.

The long time-lags now to be considered cover a range in time from a few hours to over 10 000 hours. Information about these time-lags is necessarily, therefore, only to be obtained from valves in operation.

The principal requirements for statistical study, namely, uniform conditions covering a sufficient number of definite individual cases, are fortunately well satisfied by the data provided by the large transmitter at Rugby GBR. Here the supply-voltage variations, such as they have been, are ascertainable and the modulation takes the definite form of low-speed keying. Each individual valve has an anode-current relay, and although the flashings are, of course, seldom actually observed, it is very rarely found that more than one relay has been operated. In addition to acting as indicators, these relays automatically interrupt the main power supply in about $\frac{1}{4}$ sec., so that the duration of the flash is also definite. The procedure is that after the shutdown the valve responsible is isolated; later on it is removed to a single-valve test circuit for examination, and if the result is satisfactory it is put back into operation.

Two series of results obtained in connection with this installation have already been described by Hansford.* The following results were obtained using valves of rather different construction and manufacture. They deal in the first place with the time interval for each valve of a batch between the beginning of operation and the occurrence of the first flash, and secondly with the time between replacement in operation and the second flash.

A complete survivor curve for a batch of valves, all of which have flashed once and (this is of importance statistically) none of which have failed for any other reason, is plotted in Fig. 13. The ordinates representing the number of valves surviving are on a logarithmic scale. This scale has the advantage that it makes the slope of any part of the plot a measure of the proportion

* *Philosophical Magazine*, 1924, vol 48, p. 229.
† *Zeitschrift für Physik*, 1921, vol. 8, p. 377.

* *Journal I.E.E.*, 1927, vol. 65, p. 812.

of the valves then surviving which will flash in a given short interval of time. The difficulty of indicating on this scale the time of flashing of the last valve of all is evaded by locating the observed points near the middle of the rising faces of the " steps " which constitute the " curve." This device is essential if one curve for a small number of valves is to be compared with another for a larger number.

Inspection of the plot and also of Figs. 16(*a*) and 16(*b*), which will be considered later, shows that the successive steps of the " curve " follow a fairly regular course, quite as regular as is to be expected in view of the not very large number of valves in each batch. This implies that however ignorant we may be of what is

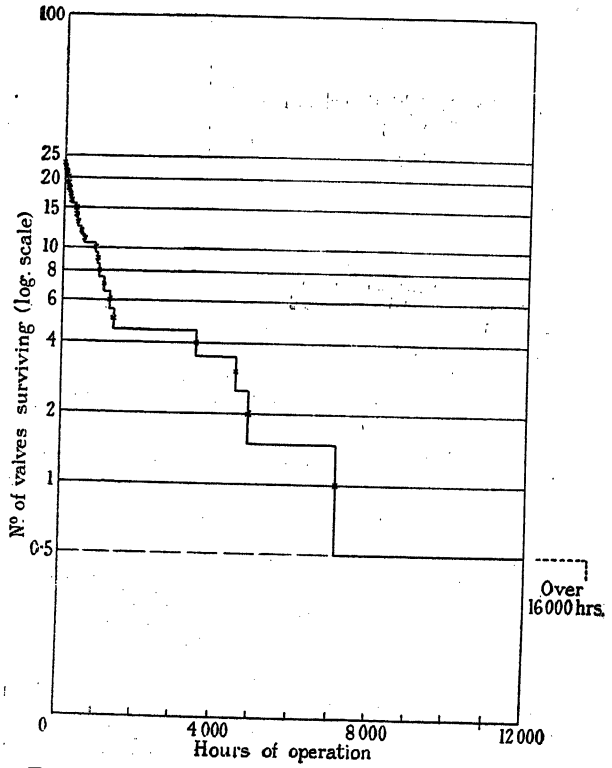


FIG. 13.—Survivor curve for 23 valves at Rugby GBR.

actually going on in any particular valve, the tendency to flash can be analysed for a group of valves so as to define certain properties, desirable or otherwise, possessed by the group.

Since most of the valves were put into operation at the same time, it might be thought that the form of the curve was influenced by possible changes in operating conditions. That this was not the case to any marked extent is shown by the fact that the lives of valves which were not put into operation until some time after the start, fit in satisfactorily with those of the original set. This is confirmed by the fact that proportionately more numerous cases of this sort occurred in batches other than those shown here. As regards the variation of anode voltage in particular, which ranged between 5 600 and 7 100 volts, it is noteworthy that the maintenance of a high value (between 6 800 and 7 100 volts) over a period of 2 400 hours (5 months' operation) produced no marked increase in the incidence of flashing. This leads to the important conclusion that where long time-lags occur, the voltage effect to which the short time-lags are so sensitive is masked by some other overriding factor. This point will be considered further later on.

As regards the time scale, since the station, although on a regular daily programme, was not operating continuously, the time variable has a certain " atomicity " with a structural unit of about 12 hours.

We can now proceed with the discussion of the form of the survivor curve. If the curve for a very large number of valves is plotted with logarithmic ordinates, the meaning of any straight-line portion of the plot is simply that the proportion of the valves surviving at any given time which flash during a fixed succeeding interval, e.g. 3 per cent in 100 hours, is constant for the valves included in that particular section of the plot. The equation of such a linear plot is

$$N = N_0 e^{-at} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where N is the number of valves surviving at time t out of the original very large number N_0. This is the form of survivor curve quoted by Hansford in connection with the two cases he describes, in which the whole plot approximates to a single straight line.

The interpretation of such a linear plot would seem, at first sight, to be quite simple and definite. It can mean that the constant a represents and defines a simple property of the group, namely, that however far the process of eliminating valves by flashing may have gone, and however long the lapse of time may have been, the fraction of the survivors which will fail in a given small interval of time is a constant.

That the group as a whole should possess this simple property is somewhat surprising; we should hardly expect the valves of a batch to be similar and unchanging in this way. Further examination shows that the similarity within a batch may be more apparent than real. Although it is certainly mathematically true that the sum of two quantities, e^{-at}, e^{-bt}, cannot be equated to an equivalent quantity of the form e^{-ct}, consideration of hypothetical cases shows that when one plots a composite survivor curve for a number of batches characterized by different constants a, b, etc., having values spread out regularly over a certain range, the form of the resultant plot cannot in fact be distinguished from a straight line. The simplest interpretation of a linear plot is not, therefore, necessarily the one to be adopted.

The plot shown in Fig. 13 is certainly not of the simple linear form, and further consideration of it is illuminating. It should be mentioned that the form characterized by a decreasing slope as we proceed down the logarithmic plot from left to right, is the shape generally found for survivor curves of batches of flashing valves, and Fig. 13 shows a case in which the change of slope is particularly marked.

The local irregularities, consequent on the comparatively small number of valves in the batches available, make it a difficult matter to follow variations of slope. It is better, therefore, to use a more suitable method than that of the simple logarithmic plot. Some unpublished work

by Ryde in this field provided several suitable functions for survivor curves of this type. If we take

$$N = N_0 e^{-bt^c} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

as a possible equation for the theoretical survivor curve, the co-ordinates used in Fig. 14 will give a linear plot.

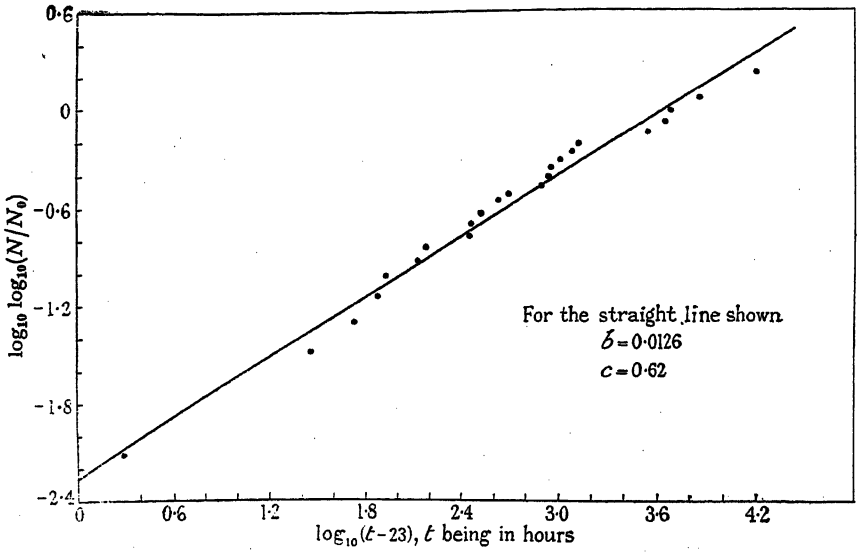


FIG. 14.—Survivor curve illustrating agreement with equation $N = N_0 e^{-bt^c}$.

Reference to this figure shows that the observed points follow a straight line fairly closely. The small adjustment provided by using $(t - 23)$ in place of t improves the fit for the three lowest points and does not appreciably affect the remainder of the curve. For other batches adjustment has not been necessary.

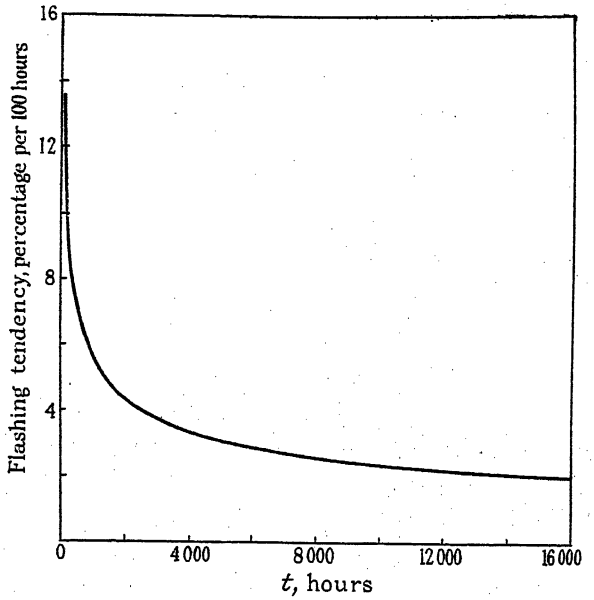


FIG. 15.—Variation of flashing tendency with time of operation.

If now we take (3) as the equation of the survivor curve, the " tendency to flash " defined as the percentage of survivors flashing in a given interval, say 100 hours, is given by the relation

$$P(t) = bct^{(c-1)} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The variation of the flashing tendency so derived from the survivor curve of Fig. 14 is shown in Fig. 15.

If c had been unity, the survivor curve would have had the simple exponential form exemplified in the cases quoted by Hansford, but the initial steep fall of the curve in Fig. 15 would have been totally absent. The condition $c = 1$, in fact, defines a singular case.

The general case, $c < 1$, brings into the statistical scheme those few and otherwise anomalous cases of flashing during the first few hours of operation which have still persisted in later batches of valves where flashing is evidently rare, although a long time yet must elapse before all the valves in these batches will have flashed and thus made it possible to plot complete curves.

Returning now to the case shown in Fig. 15, a curve of this form has two possible interpretations, which are not mutually exclusive. First, we can regard the flashing tendency as a property of the residual valves surviving at a given time after the elimination of those which have flashed before that time. The fall in the curve may thus be the result of the elimination of sub-groups of valves having a " high intrinsic tendency to flash." To define this idea more precisely, we may suppose the batch of valves represented to be a composite of sub-groups whose separate survivor curves, if there were any way of separating out these sub-groups, would have different forms such as $e^{-p_1 t}$, $e^{-p_2 t}$, etc., to take a simple case. The form of the curve in Fig. 15 implies that most of the valves would have to be assigned to sub-groups having extreme values, large or small, for these p's, representatives for the medium values being scarce.

The intrinsic tendency so defined need not vary with t (in the above example it does not), and the distinction between this first interpretation and the second one is clearest when it does not so vary. Comparative analysis

of the survivor curves of various batches of valves shows that this intrinsic tendency does probably exist.

The second interpretation has a different basis. Here we regard the flashing tendency as a property of the survivors, in the sense that its value represents a physical result of operation during a given interval of time. According to this interpretation, the fall in the curve is the expression of a progressive change during life, and a change in the direction of a diminution in the activity of the causes of flashing, whatever they may prove to be. In the latter part of this section the experimental results of a simple alteration in the procedure of operation will

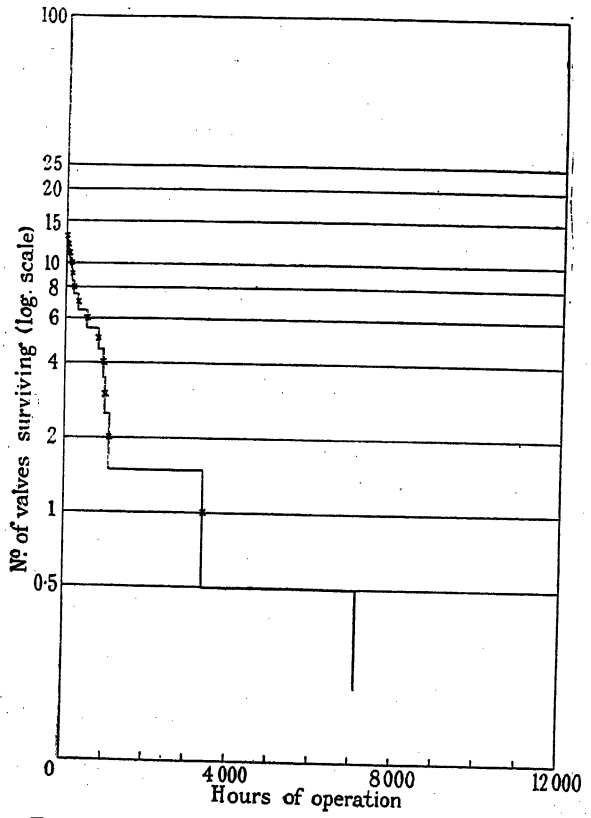


FIG. 16(*a*).—First-life survivor curve for 13 valves at Rugby GBR.

be described. These results can be interpreted as an enhancement of this favourable change.

Hence we have some support for this second interpretation also. The two interpretations, as now explained, are clearly not mutually exclusive.

To sum up, the analysis of the general form of the survivor curve (concave upwards on the logarithmic plot) reveals two possible and, as it now appears, probably co-existent, properties of valves under the conditions of Rugby GBR. These are that the valves start with different initial tendencies to flash, and that the tendency to flash diminishes during life, and particularly rapidly during the first few hundred hours.

Comparison of the survivor curve (Fig. 16*b*) for the "second lives" of valves which have been put back into operation after having flashed once, with the original survivor curve (Fig. 16*a*) for the same 13 valves (part of the batch of 23, the results of which are shown in Fig. 13), reveals another feature of the flashing tendency. The average of the second lives (1 324 hours) is nearly the same as that of the first (1 134 hours); the two survivor curves are also of substantially the same form. In the widest sense, therefore, the fact that there has been a previous flash has not, on the average, affected the second one. Such a result would follow, of course, if every valve that had a short first life had a short second one, and similarly for the long lives. This, however, is not what actually happened. Table 3, in which the valves are grouped according to the relation between the lengths of the

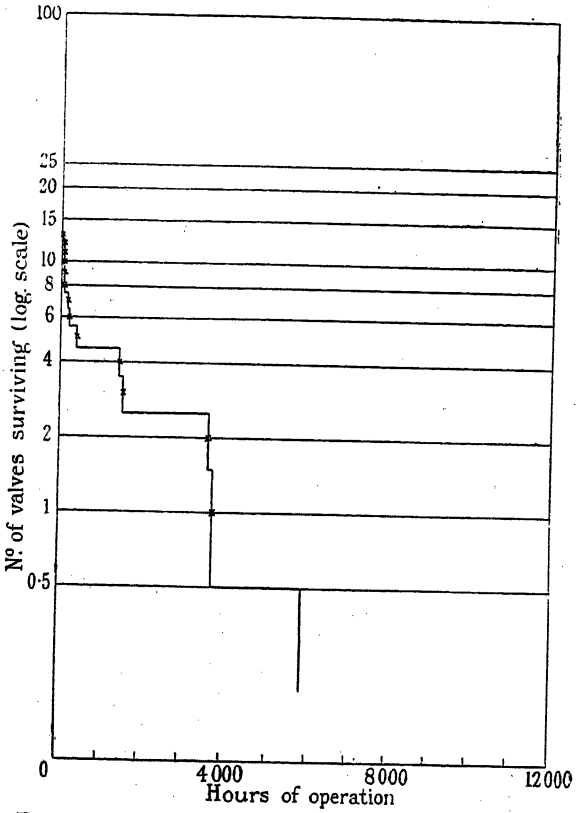


FIG. 16(*b*).—Second-life survivor curve for 13 valves at Rugby GBR.

first and second lives, shows that there is no such connection between the two.

The first flash does make a change, but the change is equally likely to be in either direction. If it were possible to arrange individual valves in order of their intrinsic tendency to flash, as shown in the first life, the arrangement would be completely re-shuffled for the second life.

This random change in the second of two long time-lags has its parallel in the changes of flashing voltage under conditions of short time-lag. Here it is found that, although the effect of a succession of weak flashes is, in general, a rise in the flashing voltage, yet if the flashes are rather more violent the reverse effect—a fall of voltage—is quite common. Thus under the right conditions a random alteration could quite conceivably occur.

Since a valve which flashes in the Rugby GBR circuit must pass very large currents, large changes in

the flashing tendency, and consequent re-shuffling of the second lives, are to be expected.

The general form of the survivor curves obtained in the course of several years of normal operation having been dealt with, an experiment which showed that this form is dependent in an important respect on a particular feature of the operating conditions will now be considered.

After the Rugby GBR transmitter had been in operation for some time, it was noticed that flashes were occurring rather more often between 8 and 10 a.m. than at any other hour of the day. Investigation showed that with very little variation some 33 per cent of the flashes occurred in this 2-hour period. Now the longest and most regular interval in the daily programme is a period of about 5 hours in the early morning, operation being resumed a little before 8 a.m. It was evident, therefore, that something which occurred during this interval was

TABLE 3.

Comparison of First and Second Lives for Valves in Figs. 16(a) and 16(b).

	First life	Second life
	hours	hours
Both lives short	147	42
	92	15
4 cases	121	25
	25	175
First life short, second long ..	173	3 617
2 cases	302	5 854
	7 124	163
First life long, second short ..	3 409	398
4 cases	959	62
	988	67
Both lives long	509	1 445
	1 091	1 552
3 cases	804	3 760

temporarily increasing the tendency to flash, and it must have been something for which a shorter interval would not suffice. Since the intervals increase the tendency to flash, they may well be supposed to do so by enhancing that overriding factor the existence of which was postulated to account for the fact that long time-lags are relatively independent of voltage. Any clue to the nature of this factor is, of course, of great practical importance.

The cooling of the hot parts of the filament and grid systems after switching off is an obvious result of the interval, and it might well have a temporary effect on the subsequent working if it went far enough. Although this cooling is rapid at first, it is a slow process when the thermal emissivity has fallen from the high value characteristic of incandescence to the very low value it has for a bright metal at a moderate or low temperature. As long as 5 hours might well be needed for cooling if the temperature of these parts had to be near that of the anode for an hour or so. These considerations suggested the experiment of restricting the cooling during the intervals by never switching off the filament completely, although, since fairly complete cooling was assumed to be necessary, it was thought sufficient to reduce the filament voltage to one-half, at any rate for the longer intervals, as this would reduce the additional power consumption and prevent needless evaporation of the filaments.

Two experiments were carried out on these lines, and both gave the same definite result of eliminating the greater part of the initial rapid fall of the survivor curve given by a number of similar valves identical in type and of contemporary manufacture, which were run as control experiments under the normal conditions of intermittent operation.

The period of operation in the intervals of which the filaments were kept hot was 641 hours in the first experiment and 701 in the second. The filaments were switched off for a time on the five Sundays included in each of these periods. These intervals did not affect the result. In the first experiment there were more control valves than experimental, and vice versa in the second. Combining the results of the two experiments, 2 valves flashed after $\frac{1}{4}$ hour and $6\frac{1}{4}$ hours respectively, i.e. before they had had time to qualify for inclusion in the experiment by having their filaments kept hot in an interval. Among the 22 valves the filaments of which were kept hot, there were no flashes at all in the 641 to 701 hours of operation, whereas among the 37 control valves operated normally with the usual intervals there were 8 cases of flashing, regularly spaced during the same period. The comparison shows that the reduction in the number of cooling periods had a very marked effect on the tendency to flash. Further, when operation of the experimental valves was continued for a further period of 1 200 to 1 500 hours in the normal intermittent way, only one flash occurred (and this after 400 further hours) among the 22 valves. Four of the control valves flashed during a similar additional period. This shows that the tendency to flash was not merely postponed; the improvement was permanent.

These experiments thus demonstrate the existence of a process of spontaneous improvement such as was suggested by the second interpretation of the generally-observed progressive decrease in the tendency to flash, exemplified in Fig. 15.

The beneficial effect of continuous operation on the reliability of valves, as revealed in these experiments, would be a matter of some importance in such cases as the use of valves or similar devices in conjunction with an ordinary power supply, where operation would be continuous.

What actually happens during the cooling period and the immediately subsequent operation is a matter of speculation, but a tentative theory may be put forward. It is well known among those engaged in the experimental study of the properties of metal surfaces in vacuo that, after being freed from gas by heating, such surfaces very readily acquire a new gas layer, even though the pressure of the residual gas in the surrounding space is kept at the lowest value attainable by modern methods of pumping. It seems that the gas evaporates from the less clean surfaces and condenses on to the cleaner, and since at these low pressures the molecules so transferred pass in straight lines from source to destination without collision with others, no pumping process can possibly

prevent condensation. Such a contamination of the previously-heated surfaces of the filament and grid system may justifiably be supposed to take place during the latter part of the cooling period. When these surfaces are heated again this gas will be set free, and will be recondensed on the colder surfaces, either spontaneously, or more rapidly by electrical clean-up during the resumed operation.

Experiment has shown that whereas free gas is not responsible for the flash-arc, cleaned-up gas can be so responsible. This is consistent with what is observed, for flashing due to cooling does not occur at once and always, but takes place during a period of some two hours, and then only occasionally. The quantity of gas necessary is suspected to be minute, and, since clean-up in water-cooled valves is particularly rapid and deals with the molecules as they are evolved, the connection of the valve to the best of pumps is not likely to provide a cure.

The relative immunity conferred by a few hundred hours of continuous operation may reasonably be ascribed to the reduction in this gas-wandering consequent on the "gettering" action of the tungsten evaporated from the filament. Conversely, the disturbance of the gettering by a flash-arc necessitates the repetition of the whole process, as in the case of the "second lives" of valves which have flashed.

In conclusion, the author desires to express his indebtedness to his colleagues, particularly Mr. L. Jacob, in connection with the superposition of the autelectronic current, and Mr. J. W. Ryde, to whom much of the statistical analysis of the long time-lags is due; to the British Broadcasting Corporation, the Marconi Co., and the Post Office, for access to their records; and to members of the staffs of those organizations for their ready assistance in the collection of data relating to the conditions and results of operation.

Discussion before the Wireless Section, 6th April, 1932.

Prof. C. L. Fortescue: I should like to ask whether the metallic-vapour arc which follows the autelectronic current consists of a bridge of gas between the two electrodes, held in position by electrostatic attraction, rather in the way in which the beam in a cathode-ray oscillograph tends to concentrate itself owing to the attraction which the positive ions have for the stream of electrons. Also, in regard to the time-lag, I find it difficult to understand the author's suggestion that this is analogous to the time-lag in mechanical yielding, and that a layer of adsorbed gas may take many thousands of hours to yield. In discussing the circuits in the various stations where flash-arc trouble has arisen, the author generally takes twice the supply voltage as the peak voltage at the anode of the valve. Under certain circumstances this value may, however, be greatly exceeded, particularly where the normal oscillation has a relatively low frequency, because there is always the chance that the valve may succeed in finding a much higher-frequency mode of oscillation. I have actually observed this effect with cathode-ray-oscillograph tubes connected to various types of oscillators, and it occurs to me that it may be in some way connected with flash-arc phenomena. Conditions within high-power valves are not as steady as our instruments would lead us to suppose, and a fortuitous combination of circumstances may set up high-frequency oscillations which are superimposed upon the peak value of the anode voltage, so causing high-frequency oscillations of amplitude much exceeding twice the supply voltage. I am relieved to notice that the author adopts the English term "flash-arc" instead of the expression "Rocky Point effect."

Mr. H. Faulkner: I obtained my first intimation that there was such a thing as a flash-arc when discussing this subject with the late Dr. Hansford on his return from America. He told me that at a demonstration of a new experimental telephone transmitter he had happened to speak into the transmitter the word "Bordeaux," whereupon the main switch had opened. This was repeated on several occasions, and the phenomenon now seems clearly to have been due to a flash-arc. The valves for the Rugby telegraph transmitter were all tested on a test set to 10 000 volts, and were then subjected to a prolonged overload test on 12 500 volts, which the valves quite satisfactorily withstood. It was intended that the valves, of which there were to be 54 (connected in parallel), should be worked on the transmitter at 10 000 volts, but the initial tests showed that this figure was too high: the "time-lag" in the case of 10 000 volts turned out to be about $\frac{1}{2}$ hour. As it was thought that the troubles were due to spurious oscillations, many circuit modifications were made—without result. Finally $\frac{1}{2}$-mm spark-gaps were inserted between the anodes of neighbouring valves, as it was believed that if intervalve spurious oscillations were occurring these would at some time produce high potentials between the valves, and so indicate their presence. On making the test, sparks were found to occur only when discharges occurred, and therefore it was concluded that most probably the valves were at fault. The working voltage was reduced to 7 000 volts, and, although since then occasional discharges have occurred, the result is not unsatisfactory. The first factor which makes the Rugby GBR circuit particularly difficult from the flash-arc point of view is that it is the highest-power valve installation in existence, 70 amperes being available for feeding into the discharge. Secondly, the wavelength of GBR is very long—about 18 000 m—and this necessitates large-capacity tuning condensers. The blocking and by-pass condensers must be of high capacitance so as to keep within reasonable limits their impedance to the working frequency. Both these features are detrimental from the point of view of flash-arcs. Even if the blocking condenser were divided as suggested in the paper, 0·04 μF would still be left. Thirdly, it is necessary to have regard to the desire of the engineers concerned to reduce interference with broadcasting, due to harmonics from this high-power station. With regard to the question of machines versus rectifiers, I agree with the author that as far as

the production of a discharge is concerned there is probably no difference; however, the fact that the machine can give 1 000 amperes whereas the rectifier can only give 100 amperes means that the after-effects on the valve may be very different in the two cases. The very efficient circuit breakers at Rugby prevent the discharges from being destructive, and machines have many compensating advantages. I notice that in the anode of each valve of Daventry 5GB (second version) there is a resistance of 550 ohms. In my opinion these resistances involve an unjustifiable loss of power; if a resistance of this size were inserted in series with each of the valves on the GBR circuit the loss would be 2 to 3 kW per valve, i.e. 100 to 150 kW in all. I should be interested if the author would tell us what steps he has taken, or is taking, to improve high-power valves. The theory advanced seems to indicate minute impurities in the filament or anode, caused by surface ruptures. I suggest that the long time-lag may result from the filament being slowly evaporated; and that this process may cause a small impurity to be suddenly uncovered, setting up a burst of current through the valve. I should like to ask the author whether he has investigated the question of eliminating impurities from filaments or anodes. In this connection it is noteworthy that the effect has not been noticed in connection with glass or silica valves, although such valves have not been used on very high-power sets to any great extent, and if the effect occurred the valve would probably be destroyed. Assuming, however, that the effect does not occur, what is the essential difference between a glass valve and a water-cooled valve? Is it a question of material or of manufacture?

Mr. H. S. Walker: It seems probable that flash-arcs may be caused by local overheating of the anode or grid structure. The valve cooling system in use at 5GB was of a somewhat primitive type and the water available was rather hard, so that scale formed rapidly on the anodes. Anode scale is a very bad conductor of heat, and the large temperature gradient across a layer of scale means that the temperature of the anode metal is many degrees higher than that of the surrounding water. A scale $\frac{1}{32}$ in. thick may cause a rise in temperature of nearly 200 deg. C., so that, assuming the temperature of the water nearest to the anodes to be 100° C., the temperature of the anode metal may be 300° C. It is probable, moreover, that the scale would form unevenly, which would cause local overheating to an even greater extent. Such high local temperatures are almost certain to cause evolution of occluded gas from the inside surfaces of the anode, and thus the production of flash-arcs may be encouraged by this gas wandering. This is also suggested by the results of the author's experiments at Rugby, where the filaments were continuously heated during the periods of transmitter inactivity. Frequent cleaning of the anodes at 5GB has been resorted to for some time, in order to prevent the accumulation of scale, and in the new Regional transmitters distilled water is employed to prevent the formation of scale at valve anodes. Overheating of the grid structure is most likely to be caused by oscillations of very high frequency. In broadcast transmissions such oscillations do occur from time to time in spite of elaborate precautions. Sometimes the causes which tend to produce oscillations of this nature are as elusive and transient in character as the flash-arc itself. These oscillations would produce currents which would possibly have a large instantaneous value and would cause overheating of the grid structure; their effect on this structure in regard to the production of occluded gas would thus be similar to that of an accumulation of scale on the anode. Has the author any facts which might lead to the conclusion that local overheating of these structures does in fact tend to produce flash-arcs? Flash-arcs have occurred almost exclusively in valves of high magnification, and it may be that valves of low magnification do not exhibit the phenomenon or that the conditions associated with these valves tend to suppress or prevent the production of flash-arcs.

Mr. F. P. Burch: It is perhaps even more difficult to arrive at the true explanation of a breakdown of a continuously-evacuated valve than of a sealed-off valve. What chiefly emerges from our experience is a confirmation of the author's statement that the mere pressure of free gas inside a valve has nothing to do with the flash-arc tendency. Another respect in which our experience agrees with the author's is that we too find the quantity of gas set free by a flash-arc to be variable and sometimes very small. The author advances the opinion that the wandering of gas has a good deal to do with the flash-arc tendency, and our experience gives a certain amount of support to that view also. If we take the " head " (the assembly of filament and grid with the insulators) of a continuously-evacuated valve that has been running for some time and put it into a new anode, we find that the valve so built up requires only a short period of treatment to get it into good condition. If, on the other hand, we put a new unused head into an anode which is in good condition, the period of treatment necessary appears to be longer (though of course not so long as when both head and anode are new). Presumably a new head requires a longer period of treatment than a new anode, because it contains metal parts which do not get heated or bombarded. The author states that flash-arcs have very seldom been observed in valves having all-glass envelopes. This being so, we must ascribe flash-arcs in water-cooled sealed valves and continuously-evacuated valves to the fact that these contain metal which has never been raised to incandescence.

Mr. A. C. Warren: In the early days at Rugby there were numerous valve overloads, and these were always classified as " Rocky Point " failures. It is only of recent years that it has been possible to classify them into various types. Even when such a classification has been made there is still the doubt as to cause and effect. For instance, have failures occurred through softness, grid filament contact, etc., or due to flash-arcs which have set up these faults? Or, further, have flash-arcs been brought about by progressive softening or distortion and disintegration of the electrodes during life, which may bring the valve into a condition at which flash-arcs occur at the operating voltage—the final discharge in this case simply hastening the deterioration? The author answers some, but not all, of these questions. The longer one's experience of water-cooled valves, the

smaller is the percentage of failures which one dares to classify as due to unpiloted flash-arcs. A case occurred at Rugby in which a large batch of valves supplied to the station had a defect in design. Valves repeatedly took overload, were tested, found to be in good condition, and were replaced; many valves finally failed due to grid-filament contact. In this batch were found extreme examples in which a valve would take overload 2 or 3 times in the first 100 hours, and then would continue to operate satisfactorily for thousands of hours without taking overload: or a valve would take a first overload after thousands of hours, and then take overload repeatedly every few hours. An examination of the records for this batch shows that the tendency to failure increased with life. This type of behaviour is abnormal, and only occurs when manufacturing defects are present. With this proviso, I am in agreement with the author's conclusions regarding time-lags, namely that the tendency to flashing decreases with life and that there is no relation between the first and the second life. This latter point is borne out by the lives of new and repaired valves. The Post Office has adopted the policy of having valves repaired, and it is found that the average life after repair is greater than that of new valves; also that the lives of valves after repair bear no relation to the lives of the new valves. Although these lives include all classes of failure, it is felt that the facts stated above have some bearing on the present discussion. As the repair of a valve involves opening it up to atmosphere and renewing the filament, it would appear that the filament and gas pressure of the valve are not determining factors in flash-arcs. The paper puts forward no cure for flash-arc troubles. It would be interesting to know the minimum voltage at which discharges can be set up, and the actual currents measured by the author. Although he states that 3 watt-seconds are dissipated in building up the conducting path, he does not say whether this amount of energy can be provided by a 1-farad condenser charged to 2 or 3 volts, or whether a certain minimum voltage is necessary. The effect of electrode dimensions is not mentioned, although this is apparently of extreme importance. The interesting tests at Rugby on the continuous burning of filaments in early life were suspended on the score of economy, the valves being so good—even on intermittent burning—that the improvement to be obtained was slight. This mode of operation might be very useful if a poor batch of valves were encountered.

Mr. W. L. McPherson: I agree with the author that pumping does not seriously affect the liability of a valve to flash-arc; at the time when this effect was so prominent at Rugby, the first conclusion we came to was that it must be caused by a poor vacuum. The improvement effected since those days has been chiefly an advance in the direction of greater cleanliness in the materials and in the assembly. The author states that trouble is experienced in connection with 2-phase, 4-phase, and 6-phase rectifiers, and I should like to know the type of 6-phase rectifier to which he refers in this connection. We have used a high-power 6-phase rectifier with interphase reactor without encountering any difficulty. The high-voltage effect is a function both of the valve and of the circuit in which it is used, and, in spite of Mr. Faulkner's remarks, spurious oscillations which may have a trigger action are liable to occur and so exaggerate any latent tendency to flash-arc. The general experience is that as the power of the station increases, the safe voltage for a given type of valve decreases. The Prague broadcasting station, which is operated at 18 000 to 20 000 volts, has given very little flash-arc trouble. Coolidge has succeeded in making triode valves and X-ray tubes for voltages as high as 100 000 volts, and I should like to know whether there is any evidence of the presence of flash-arc effects in such apparatus.

Mr. L. J. Davies: I should be glad of the author's views as to the part that gas adsorption plays in the flash-arc and in the mechanism of the pilot discharge. Is it correct to state that it is a metallic fragment that vaporizes and gives off gas? Does the adsorbed gas merely loosen the surface atoms of the metals and enable them to vaporize more easily?

Mr. H. L. Kirke: At 5GB practically no trouble from flash-arcs occurred until the number of valves was increased from four to six. This change was made when the station first began to transmit the official programmes, and thereafter we often met with a dozen flash-arcs during an afternoon. Although, as Mr. Faulkner stated, a 1½-minute shutdown may not matter much so far as telegraphic communication is concerned, from the point of view of broadcasting a shutdown of a minute or so may be very important. As regards the question of spurious short-wave oscillations, it seems to me a reasonable supposition that, if a valve has a tendency to flash-arc, the increase of potential due to the short-wave oscillation may start the flash-arc discharge. The phenomenon of spurious oscillations in transmission is one of the most elusive things with which a radio engineer has to deal. I was very disappointed that the circuit change-over at 5GB occurred almost at the same time as the improvement in the design of the valve, and I have always felt a desire to try the new valves on the old circuit. In my opinion the recent big improvements in valves should make possible a considerably simplified design of transmitter. Turning to the question of the resistance in the anode circuit of each valve, we have reduced the value of this resistance to 250 ohms in the types of valves now manufactured, so that the kW loss in these resistances is relatively small compared with the total power. An interesting characteristic of 5GB was that if during the course of the morning's experimenting and testing we applied a fairly heavy modulation by pure tone for any appreciable time, a batch of flash-arcs nearly always occurred during the afternoon; but if we only carried out ordinary modulation testing during the morning, we encountered very little trouble in the afternoon. The other day, during some tests on the change of circuit at Brookman's Park, we met with the same trouble, probably due to a flash-arc.

Mr. B. S. Gossling (*in reply*): From remarks made in the discussion I gather that it would be profitable to open this reply with an account of my speculative mental picture of the flashing process. The part of the picture showing the first stages of the flash is still rather vague; what I should put there is an autelectronic current spontaneously appearing or increasing in value. This impinges on the anode and produces positive ions from

the metal, or at first, more probably, from some more easily dispersible surface layer such as adsorbed gas (in answer to Mr. Davies). These return to the cathode, bombarding it (still at high voltage) and producing many more electrons, and also neutralizing space charges, thus reducing the voltage demanded by the growing current. The autelectronic stage might give a current approaching 1 ampere, which is about enough to render possible an incipient arc. Then follows a true metallic-vapour arc very much like that in a mercury-arc rectifier, capable of carrying enormous currents. There is no difficulty about the maintenance of the conducting bridge surrounded by a vacuum, because the speeds attained by ions in very moderate electric fields are enormously greater than the kinetic-theory speed of molecular diffusion, even in a hot vapour. The analogy between this final stage and the mercury-arc rectifier becomes closer when we consider such a rectifier starting with a heavy current while in a cold state. The pressure of the mercury vapour is then far below the normal working value, and the highly-conducting bridge has to be maintained, as in the flash-arc, by material vaporized from the cathode, unidirectional diffusion to the surrounding space and the cold walls being little more impeded than in a high vacuum.

In answer to Prof. Fortescue's first query, space charge would certainly tend to dissipate the gas bridge laterally unless it were effectively neutralized by the presence of charged particles of both signs; hence the need for positive ions derived from the anode surface in the early stages of building-up. Later on, however, when the current density is large, possibly enormous, the local magnetic field will act so as to prevent straying of the ions, just as that of the heating current of a thick filament tends to bring electrons back to the emitting surface.

My account of the " mechanical rupture " theory of the short time-lag was somewhat condensed, but the " yielding " considered is supposed to be a true mechanical yield, on a small scale no doubt, but something more concrete than the disruption of a gas film, since it is a solid fragment that is supposed to be detached. The rupture is on the surface of the cathode, and provides the autelectronic beginning of the flash; the gas film is on the anode, and provides the ionization required by the embryo arc. The theory is associated in the paper with the short time-lags only; it is not incompatible in principle with a long lag, but the independent experimental evidence quoted does not go far in that direction.

I should next point out that my intention in the paper (Section 13) was to confine the term " piloting " strictly to abnormal cases in which some auxiliary discharge capable of acting in substitution for the normal initial stages was known to be present. A mere enhancement of conditions favourable to the spontaneous flash-arc, which is the main subject of the paper, does not constitute " piloting " in this restricted sense.

The general impression produced by the references of various speakers to parasitic oscillations is that so far little profit has been gained through explaining one mystery by means of another. The possible types of parasitic oscillations are no doubt many and various, but Mr. Fortescue's ocular demonstration of over-voltage directs suspicion against one type at least. Again, his suggestion that a " Schrot-effect " variation of the characteristics might make the appearance of a parasitic oscillation a matter of random probability is interesting, but the designer of circuits should take heart from the reflection that this probability decreases very rapidly as the circuit conditions depart from the critical values based on " average " characteristics.

Many of the conclusions given in the paper are as yet tentative rather than properly established, and it is therefore the more satisfactory to have the confirmation given by the independent experience of others. Notably Mr. Burch, with the different and more direct technique of the continuously-exhausted valve, supports the absence of effect due to free gas. The conclusion which he draws from the results of interchanging new and old electrodes gives a direct answer to Mr. Faulkner's question about the difference between glass and metal valves. It bears out my own inference that this difference was a matter of the relative absence of cold unbombarded surfaces in glass valves.

Again, in answering Mr. Faulkner's query as to means of improvement, I have Mr. McPherson's support in the matter of cleanliness. I would add an important if unimpressive desideratum which he no doubt took for granted, namely, the avoidance of unconsidered changes in procedure, however trivial in appearance. As regards more recent types of valves than those considered in the paper, it is as yet impossible to ascribe the undoubted improvement to any one of the various modifications embodied in these valves.

As regards gas wandering, Mr. Burch replies to my mild provocation by giving me his support; I cannot but admit that if gas wandering may happen on the pump, it is at least not less likely in a similar sealed valve. Still, there need not be much difference, because the clean-up may act very much more quickly than the pump. Mr. Walker gives two very probable causes of encouragement of gas wandering, and other radio engineers should take warning from him. Grid overheating such as he suggests would act as a novel form of intermittent operation; indeed, this, and also the prolonged heavy modulation (doubtless implying extra grid heating) described by Mr. Kirke, seem to provide the converse to the Rugby continuous-burning experiment and to promote flashing, also after an interval. I would follow Mr. Warren so far as to suggest a further cause for progressive increase in the flashing tendency, namely, that valves which soften progressively—as no good valve should—might show such an increase owing to enhanced gas-wandering. However, I should not describe this as " piloting."

In reply to Mr. Faulkner, adsorbed gas which has any opportunity of wandering is by far the worst type of surface impurity. Volatile impurities from filament or grid should be disposed of before or during exhaust; as stated, the volatilized tungsten seems to be beneficial.

As to the question of magnification, raised by Mr. Walker, valves of low magnification do flash, although fewer valves of that sort are in use and those are in the lower-power stages.

Mr. Kirke's observation on the change from four valves to six seems to define the permissible limit of concentration of H.T. supply current quite closely at between

7 and 9 amperes for the smaller sizes of valves. Mr. Faulkner seems to have overlooked the fact that if the Rugby GBR circuit were subdivided, this concentration, which is the most dangerous factor there, would be disposed of; condensers of 0·04 μF might not be dangerous alone. I agree, however, that a change from capacitance tap to inductive tap would have little or no effect at GBR, as the equivalent inductive tap there would have so little self-induction. The anode resistances on the supply side, like the use of rectifiers instead of d.c. machines which Mr. Faulkner himself cites, are of value only in minimizing after-effects, and are only justifiable where some efficiency can be sacrificed in order to reduce the time of shutdown. The sacrifice is, of course, less the higher the supply voltage.

In reply to Mr. Warren's general comment, I admit the difficulty, but I did scrutinize individually the nature of the failures quoted in Section (24). These included no cases of filament distortion prior to flashing and therefore no "piloting" in my sense of the word, and but few cases of serious softening, so that as a batch they were well suited to my purpose. The statistical results obtained would not, however, have been seriously affected if, say, two or three failures had been in a different class from the rest.

The magnitude of the currents I measured was, for brevity, left to be inferred from Table 1. Column 4 of the table shows that with charging voltages of 50 to 60 kV in the first circuit, currents approaching 100 amperes were possible, and in the third with 20 to 30 kV, 300 to 500 amperes.

As to the minimum voltage, the initial stages of the spontaneous flash-arc are high-voltage phenomena, otherwise their autelectronic origin could not have been seriously suggested; I do not think I have observed such flashes below 9 or 10 kV. In the presence of a glow discharge, where the initial stages are probably different and the initial expenditure much less, flash-arcs can be obtained at voltages as low as 200 volts.* The inductance in circuit with a condenser must be low enough for the energy to be quickly available; with a condenser as large as 1 farad this would hardly be possible.

In answer to Mr. McPherson's later remarks, my own experience had not led me to consider the 6-phase rectifier with interphase reactor specially immune from trouble, but definite statistics for rectifiers are hard to obtain. His statement as to stations of higher power confirms the conclusions summarized in Section (21). However, the Warsaw broadcasting station has now (June 1932) been working at 14 to 15 kV for nearly a year with very little trouble.

Apparatus of the 100 000-volt sort will give flash-arcs plentifully, but as the power supply, and particularly the short-circuit current, is relatively small, they are transitory and often inconspicuous. It was in the high-power radio field that flash-arcs were troublesome.

* *Nature*, 1928, vol. 121, p. 794.

SHIPBOARD OBSERVATIONS WITH A CATHODE-RAY DIRECTION-FINDER BETWEEN ENGLAND AND AUSTRALIA.*

By G. H. MUNRO, M.Sc., Associate Member, and L. G. H. HUXLEY, M.A., D.Phil.

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SUMMARY.

The paper describes the installation of a cathode-ray direction-finder on board a ship and observations on long-wave stations and atmospherics during a voyage from Port Said to Brisbane.

Directional observations of long-wave wireless stations at distances of from 1 000 to 5 000 miles showed little evidence of errors in bearings, and the bearings obtained were compared with the calculated ones to find the quadrantal error due to the ship.

Systematic daily observations of atmospherics on 30 000 metres gave intersections suggesting tropical thunderstorm areas, particularly one in Central Africa, as the main sources during most of the voyage, but round the coast of Australia the predominant sources were in the northern interior of that Continent. The directions of these sources in Australia are shown to correspond to areas of low barometric pressure accompanied by thunderstorms in those regions.

(1) INTRODUCTION.

The theory and use of the usual types of direction-finder have been treated in detail by several authors,† but shipboard observations with a cathode-ray direction-finder have not previously been described.

In December 1929 a cathode-ray direction-finder constructed at the Radio Research Station, Slough, was to be shipped to Melbourne as part of the equipment to be used in an investigation of atmospherics in Australia, and as the authors were sailing at that time to carry out the work an opportunity was afforded to test the instrument on board ship and to observe atmospherics through the tropics. By the courtesy of the P. & O. Branch Line it was possible to install the instrument on the s.s. " Baradine." Observations were begun when nearing Port Said, and were continued the whole way to Australia and round the south and east coasts of that Continent as far as Brisbane. An account of these observations is given below.

(2) THE CATHODE-RAY DIRECTION-FINDER.

The instrument was of the latest type, developed at the Radio Research Station of the Department of Scientific and Industrial Research for observing the direction of arrival of individual atmospherics. Although it has been described in " Report of the Radio Research Board for the period ended 31st March, 1929 " a brief account of the instrument is given here in order to simplify the subsequent descriptions.

Two identical frame aerials (Fig. 1) are mounted with their planes vertical and mutually perpendicular, and are adjusted to have no mutual inductance. The frames are 1 metre square and are tuned with variable capacitances to cover a wavelength range of 3 000–30 000 metres.

The electromotive forces induced in the aerials receive separate and equal amplifications and are applied respectively to the two pairs of deflecting plates of a cathode-ray oscillograph.

Let a plane polarized electromagnetic wave whose electric vector lies in the vertical plane arrive at the instrument along a direction making an angle θ with the frame n–s (Fig. 1). The e.m.f.'s induced in the two

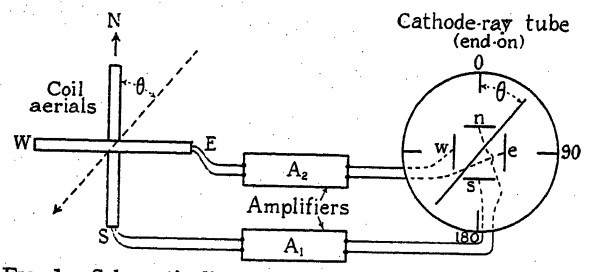


FIG. 1.—Schematic diagram of cathode-ray direction-finder.

aerials n–s and e–w are proportional respectively to $\cos\theta$ and to $\sin\theta$. The output from the n–s amplifier acting alone spreads the spot on the oscillograph dial into a vertical line whose length is proportional to $\cos\theta$, whereas the e–w amplifier output gives a horizontal line of length proportional to $\sin\theta$. Both amplifiers acting in conjunction give a linear trace on the dial at an angle θ with the vertical when the output e.m.f.'s are in phase. Since the dial is calibrated at intervals of 10° the direction of arrival of the incoming wave relative to the n–s frame may be read directly. The strength of the signal is also correctly given by the length of the trace on the dial, but there is an ambiguity of 180° in the angle θ.

The e.m.f.'s in the aerials are heterodyned with the e.m.f. from a local " beat " oscillator to give a " beat " frequency of $2\frac{1}{2}$ kilocycles per sec. which is introduced into the amplifiers. The amplifiers incorporate devices for controlling the total amplification (gain) and for eliminating spurious differences of phase between the output e.m.f.'s. There is also a " test " oscillator from which electromotive forces of suitable frequency and

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† For example, R. KEEN: " Wireless Direction Finding and Directional Reception," 2nd edition (Iliffe); also R. L. SMITH-ROSE: " Radio Direction Finding by Transmission and Reception "; and International Scientific Radio Union, collected papers of Brussels Assembly, 1928.

strength may be introduced into the aerials across 1-ohm non-inductive resistances at their centres.

The instrument is in adjustment for receiving a wave of given frequency when the injection of equal e.m.f.'s of that frequency into the tuned aerials from the "test" oscillator produces a line at 45° on the oscillograph. If a spurious difference of phase is present the line is replaced by an ellipse, and if the amplifications are unequal the line is not at 45°. These inequalities are corrected by the devices mentioned above.

(3) Location of the Instrument on the Ship.

The instrument was mounted on the "Baradine" in a position which was fairly satisfactory, though not ideal. A substantial and light-proof house for the receiving apparatus was constructed on the captain's deck below and abaft the bridge. The frames were mounted on the roof of this deck, which was of wood and canvas, and at its starboard end since the frames' aerials of the ship's direction-finder were mounted amidships on this roof. The only objects near the aerials which could distort the bearings were a tall iron ventilator aft and an iron boat davit to starboard, while the bridge, although further away, was a possible source of error. The effect of any of these was, however, likely to be small compared with that of the ship as a whole.

(4) Observations on Stations.

It was not possible to install the aerials before sailing, and on account of adverse weather conditions the preparations were not completed until near Port Said, where the observations were initiated.

In the Suez Canal and the Red Sea transmissions from a number of European stations were received at good strength, and their bearings were readily obtained. Those observed were: FYL (Bordeaux); GBR (Rugby); DFY (Nauen); PCG (Holland); TAE (Turkey); SPL (Warsaw); FYN (Lyons); and IBR (Rome), the wavelengths ranging from 19 000 to 14 400 metres. In the Indian Ocean the intensity of these stations was much less, but FZD (Madagascar); PKX (or PLA) (Java); and FZA (Saigon) were received sufficiently well for observations to be taken on them all the way to Fremantle. South of Australia the reception of these stations was unsatisfactory and JND (Japan), which was also well received in the Indian Ocean, alone gave signals of strength sufficient for good observations.

On land the angle given by the oscillograph may be read to an accuracy of 1 degree, but at sea the accuracy was less satsfactory owing to interference of two types:

(*a*) Electrical interference caused by the ship's electrical installation.

(*b*) Mechanical vibration of the ship communicated to the valves of the receiver.

The blurring of the spot on the dial of the oscillograph through the operation of these factors, of which the former is the more serious, amounted to about ½ cm in the athwartships' direction and about 1 cm in the fore-and-aft direction at full sensitivity. This produced a corresponding broadening of the line on the dial during the reception of a transmission. Fortunately, one-sixth of the maximum amplification was suitable for the reception of stations of reasonable strength, and with this setting the broadening of the line was not serious. The instrument could then be read with an accuracy of ± 1° in the absence of atmospheric interference.

It was found desirable with transmissions of good strength to adjust and "line up" the instrument directly on the station instead of using the "test oscillator."

On occasions the deposition of salt spray on the aerials impaired the insulation. This resulted in an inequality and an increase in the effective resistance of the aerials, which were manifested in an incorrect "line up" and loss of sensitivity. The inequality in the resistances of the aerials was easily eliminated by inserting a variable series resistance until the aerials could be washed with fresh water.

Well defined bearings were generally obtained on stations received with sufficient strength, both by day and at night, and on few occasions only was any ellipticity observed which was attributable to abnormal polarization.

In addition to the inaccuracies mentioned above, the bearings observed relative to the ship are subject to the usual "quadrantal error" of the ship itself, and in order to correct for this the installation was calibrated from observations of stations whose locations were known. The course, or "ship's head," was obtained from the navigating officer, and the accuracy of the bearings obtained depended on the constancy of the course at the time of observation. The error due to variation in the course did not exceed ± 2 degrees, though rolling or yawing could cause greater variations.

When the "ship's head" was known the true directions of stations relative to it could be calculated from their geographical positions and that of the ship at the time of observation. By comparing these bearings with those given by the direction-finder the errors due to the ship and the installation are obtained. The results obtained for the various stations mentioned above are shown in curve A of Fig. 2, in which the error is plotted against the calculated correct bearing.

It will be seen that the majority of the points agree with the average curve. The series of high points between 260° and 300° and that at 111° were all obtained during a period when trouble was experienced with the insulation of the aerials as already mentioned.

An opportunity for rapid calibration occurred at Adelaide when the ship swung through 180° before anchoring, and again on resuming the passage down the channel. Bearings of the station JND given by the instrument were obtained by one observer, while the other observer in communication with the first recorded the series of corresponding readings on the standard compass. The "ship's head" was obtained from the standard compass and the necessary corrections supplied by the navigating officer. The results are given in curve B of Fig. 2, where the errors are again plotted against the true bearings.

Again the points lie close to the average curve, but there is some discrepancy between the curves A and B, more especially between 260° and 360°. Curve C is an average curve obtained from A and B. Owing to the ambiguity of 180° in the reading of the instrument a further average is taken of the errors in the ranges 0–180 and 180–360 to make the curve symmetrical in

these ranges. Curve C was used in correcting atmospheric observations. Curve D is the curve derived from it, showing the corrections for given observed bearings.

"Quadrantal error" associated with direction-finders on ships has been examined theoretically by R. Mesney* by treating the ship as an infinitely long conducting cylinder of radius small compared with the wavelength received. The matter has also been treated from the practical point of view by C. E. Horton.†

According to Mesney the maximum error will be

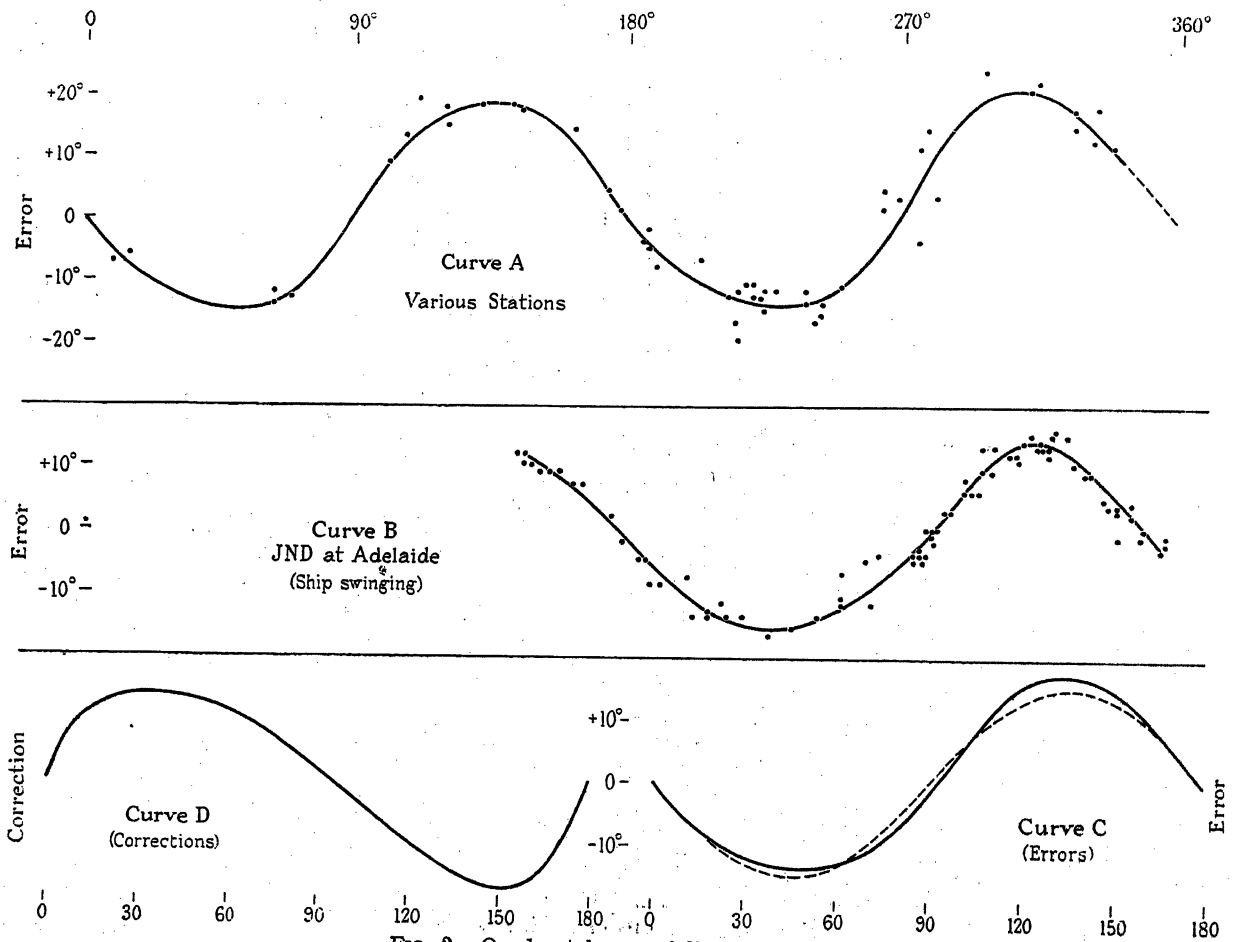


FIG. 2.—Quadrantal error of direction-finder.

18·5°, a value which is exceeded in our case. The discrepancy is probably due to the superstructure of the ship in the vicinity of the aerials. Mesney also deduces the result that the error is independent of the wavelength when the latter is great compared with the length of the ship. This is in agreement with our curves. It is assumed, therefore, that the correction curves apply to wavelengths up to 30 000 metres, and are applicable to the reception of atmospherics on this wavelength.

These observations show that the cathode-ray direction-finder at sea is capable of giving accurate results in the bearings of long wavelength stations, and in this respect is superior to the usual types of direction-finder. It also has the advantage of giving the required bearing directly by a visual reading. On the other hand, compared with the usual ships' direction-finders it has several disadvantages. It is extremely bulky, it requires voltages of the order of 300 volts to operate the oscillograph, and it must be operated in the dark. These facts, when taken into consideration with the short life of the cathode-ray oscillograph, must be considered to be serious disadvantages in this type of instrument.

(5) Observations on Atmospherics.

Owing to the limited life of the oscillograph, observations were restricted to regular brief periods. Atmospherics were observed for 5-minute periods at intervals of about 4 hours between 8 a.m. and 11 p.m. during most of the voyage.

Directional observations on atmospherics were begun on the 20th December, 1929, when the ship was in the Mediterranean Sea, one day before reaching Port Said, and were continued daily with a few exceptions. At first the observations were taken at 1230 G.M.T. but the number of observing periods was later extended to obtain information concerning the diurnal variations. A standard sensitivity of the receiver was used. At first it was sufficiently accurate to use always the same

* *Radio Review*, 1920, vol. 1, p. 533.
† *Journal I.E.E.*, 1928, vol. 61, p. 179; and 1931, vol. 69, p. 623.

setting of the " gain " controls, but later, owing to variations in the aerial resistances, this was not a reliable measure of the overall sensitivity, so a particular setting of the " test " oscillator output control was used, and the amplifiers were adjusted to give a full-scale deflection on the signal injected into the aerials from this oscillator. The sensitivity at this setting was such that a full-scale deflection would be produced by a signal of field-strength of the order of 1 millivolt per metre.

For convenience in recording, the atmospherics observed were separated into four sizes according to the length of the line produced on the screen, thus: S up to 1 cm; M, 1 to 2 cm; B, 2 to 4 cm; and L greater than 4 cm. Each individual was recorded as a letter followed by a number giving the size and direction in degrees (0 to 180°) respectively. It was usual to note as many as possible of those occurring within a period of 5 minutes. It was frequently impossible to note every one, and care had to be taken to get a fair sampling. If there is a predominant source in one direction it tends to hold the observer's attention to the exclusion of less active sources. In such a case this direction was neglected for part of the observing period and attention concentrated on arrivals from other directions. After a few days' practice the directions on the screen could be observed under the best conditions to within $\pm$ 1 deg. for a B or L, $\pm$ 2 deg. for an M and $\pm$ 5 deg. for an S. The maximum accuracy was not attainable in general, and, as there is a strong tendency to take the direction as the nearest multiple of 10 or 5, it is found that the great majority of recorded directions, even for L's and B's, have 0 or 5 as the last digit. 2 and 8 occur fairly often and other numbers only occasionally. Sets of observations for consecutive 5-minute periods by the two observers in turn showed very satisfactory agreement in the sizes and distribution recorded, so that in considering the results no distinction is made. The maximum observational error for a single atmospheric other than S is estimated as $\pm$ 3°, so that the mean error will be less than that. Individuals have accordingly been plotted to the nearest degree. Graph paper divided into millimetres was used for plotting, each vertical line being taken to represent 1° of bearing, and each atmospheric plotted under the appropriate bearing as a dot if M or S, a line 1 mm long if B, and a line 2 mm long if L. The number and size of all observed in any direction is thus at once apparent. The corrections for quadrantal error and ship's head have then been applied and the individuals replotted to the nearest multiple of $2\frac{1}{2}$°, since it is estimated that the mean accuracy for a point source will be greater than $\pm$ 5° but less than $\pm$ 1°. The results shown in Figs. 3 and 4 are obtained in this way.

In considering the results obtained it has been found that they may conveniently be studied in three sections according to the areas in which the observations were taken, the areas being: North of the Equator, the Indian Ocean between Colombo and Australia, and round the Australian Coast. Taking the first group, the results of observations at or near 1230 G.M.T. from the 20th December to the 4th January inclusive are shown in Fig. 3. It will be seen that, except on the first two and last two days, there is always one predominant group restricted to quite a narrow angle, and that the mean direction of this group changes as the ship proceeds. (In discussing results the term " Source " will be used as applying to an area in which atmospherics are originating and which subtends in general an angle of less than 10° at the observing station; while " Group " will be used as applying to the concentration of dots or lines in one direction when the results are plotted, due to one or more such sources in the same or opposite directions.) When the directions of the centres of these groups are drawn in on a map they are found all to pass through or close to a point in the lower part of Central Africa, and, moreover, if the limiting directions for the group on each day are drawn they enclose a definite area in that location. This is shown on the map of Fig. 5. In Fig. 3 the crosses indicate the directions taken as the limits of the groups for this purpose. On the 28th December not many atmospherics were observed, but it was noted that a source was developing at 65°. On the 31st December no individual observations were taken, but it was noted that the activity was confined to the angle indicated between the arrow-heads. On the 1st January the observations were meagre but are sufficient to show the direction of maximum activity. After this date the lower limit of the group is not very well defined but it will be shown that this is probably due to other sources in an almost opposite direction. On the 2nd January the observations plotted were taken at 1130 G.M.T.

Since it has been concluded by various investigators, in particular by Watson Watt, that thunderstorms supply the great majority of, if not all, the atmospherics of the world, it is of interest to examine the frequency of thunderstorm occurrence for this area. Information on this point is given in a convenient form by Brooks who divides the year into two periods and draws " isobronts," or lines of equal frequency of occurrence of thunderstorms, expressed as the percentage of the total days for the period on which thunderstorms are reported at observing stations. The resultant map for the period October to March shows that by far the most active thunderstorm area in the world is in Africa just in the area defined by the atmospherics. In the centre of this area thunderstorms occur on 50 per cent of the days at all stations. The isobronts for 50, 30, and 20 per cent are indicated in Fig. 5. There thus seems to be little doubt that the thunderstorms of this area were supplying most of the atmospherics observed during this part of the voyage.

From the 26th to the 31st December a set of observations was usually taken several hours before 1230 G.M.T., and a further set several hours after. In the earlier ones, between 0400 and 0800, there was generally a predominant group at about 100°, which is the direction of the ship's course. This group was absent or less in evidence in the 1230 or later observations. Since it is well established that the maximum production of atmospherics in any area occurs in the local afternoon, it is assumed that this group was coming from the east, and the direction is shown accordingly on the map. The observations after 1230 G.M.T. showed little other change except, in some cases, an intensification of the main group.

Referring to Fig. 3, it is evident that from the 26th

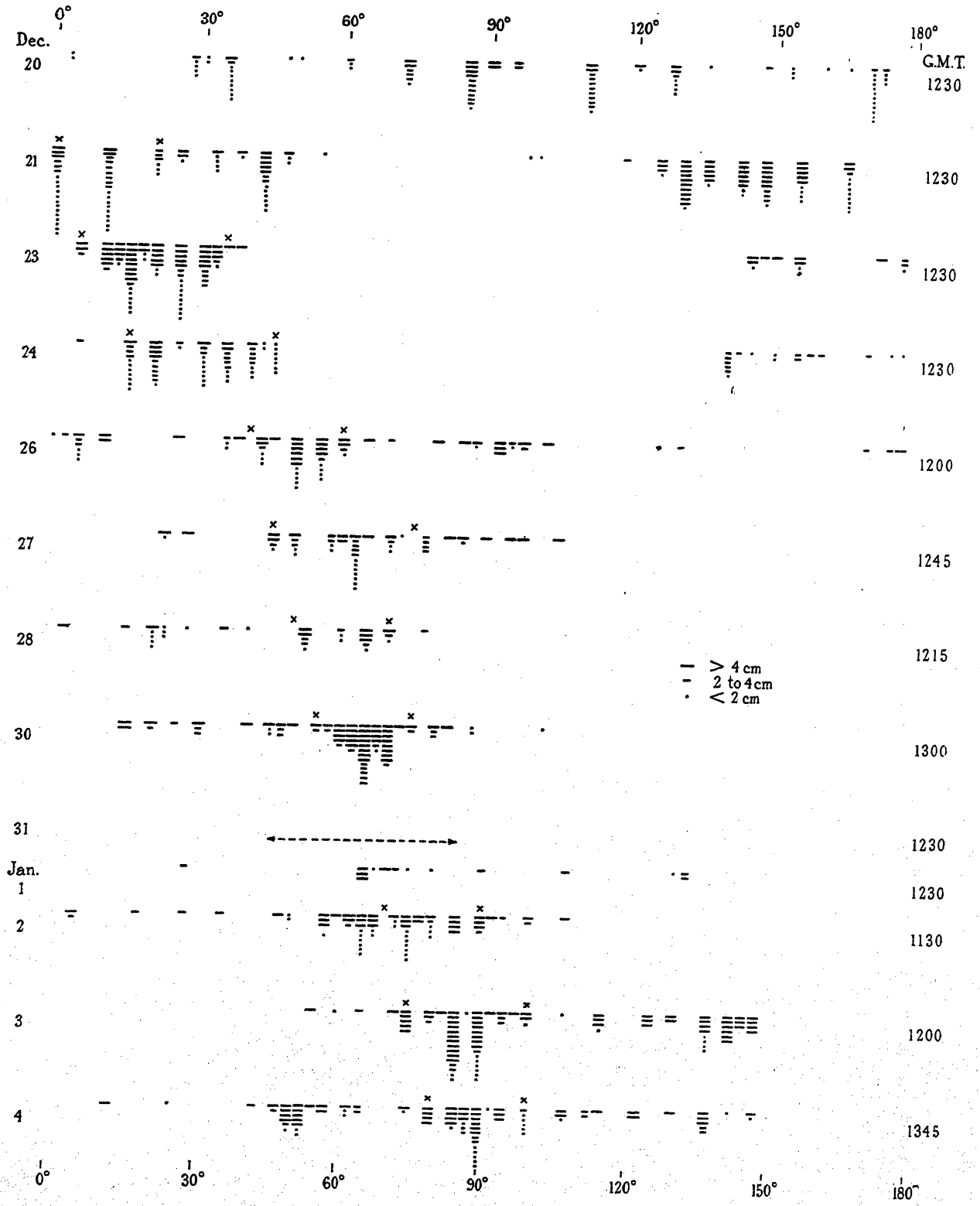


FIG. 3.—Atmospherics observed on 30 000 metres.

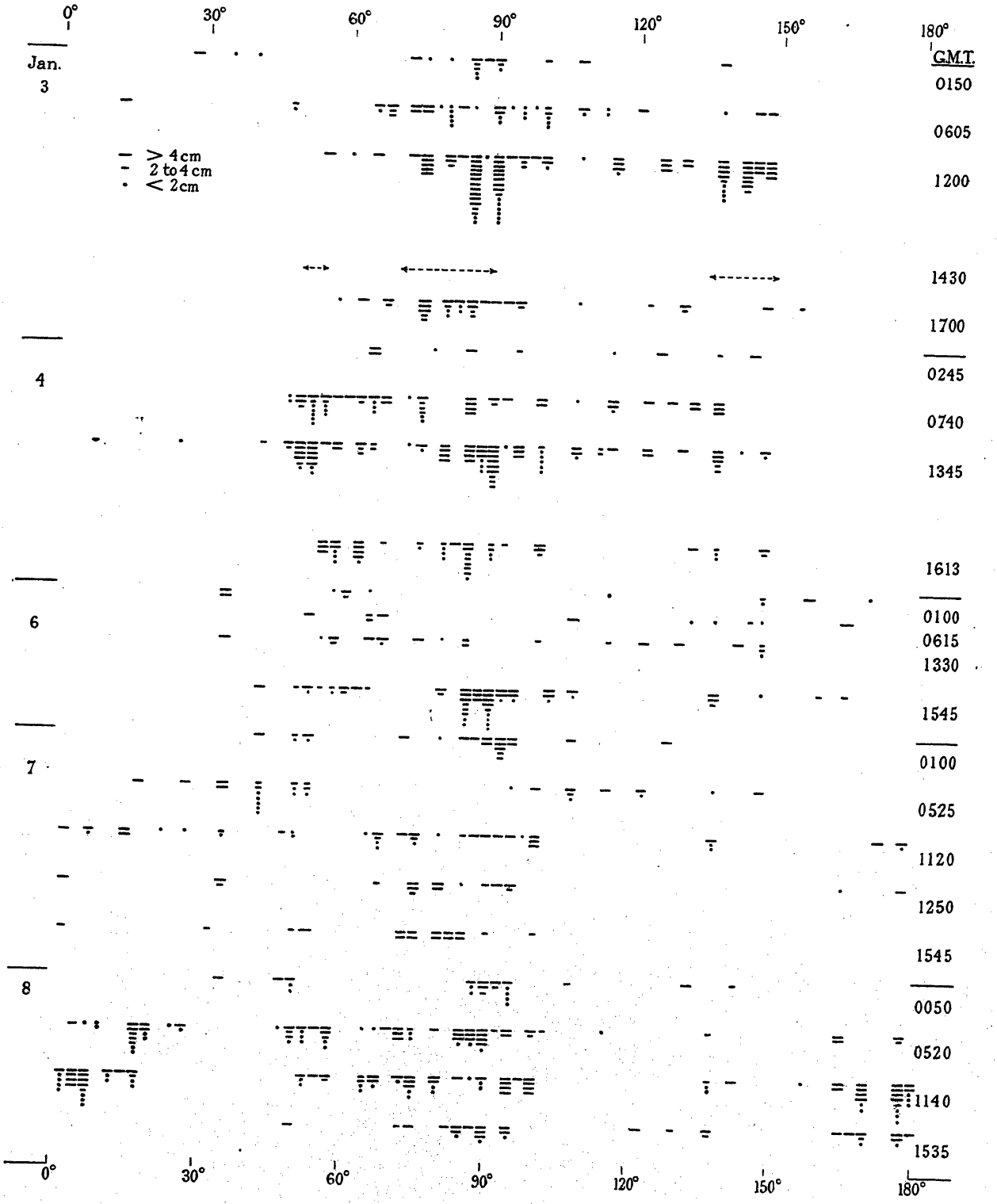


FIG. 4.—Atmospherics observed on 30 000 metres: Indian Ocean.

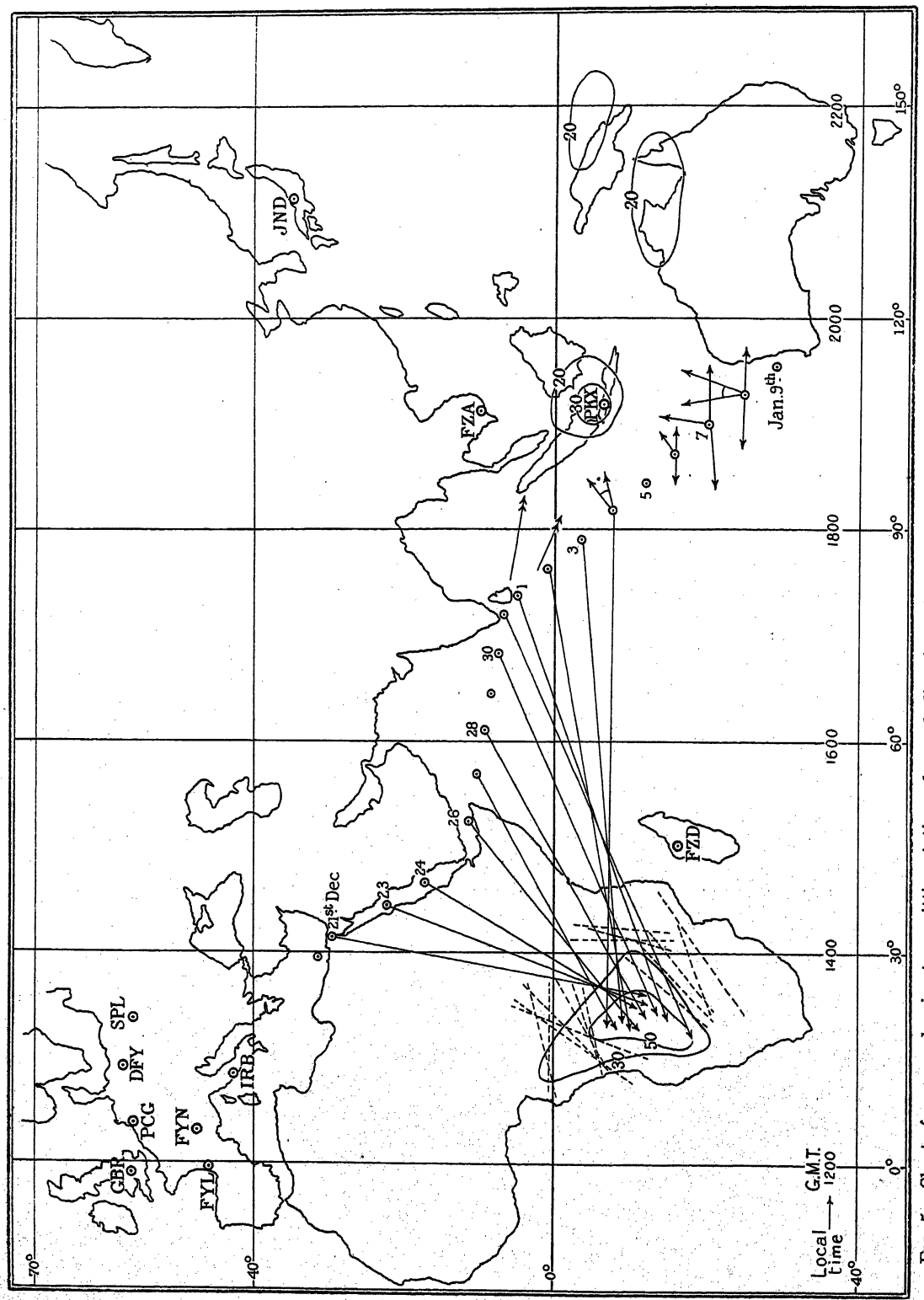


FIG. 5.—Chart of voyage, showing transmitting stations observed, directions of atmospherics at 1230 G.M.T. daily, and main thunderstorm areas in these longitudes.

NOTE.—Arrows denote directions of maximum activity. Dotted lines mark limits of groups. Figures on isobronts give percentage of days on which thunderstorms are reported.

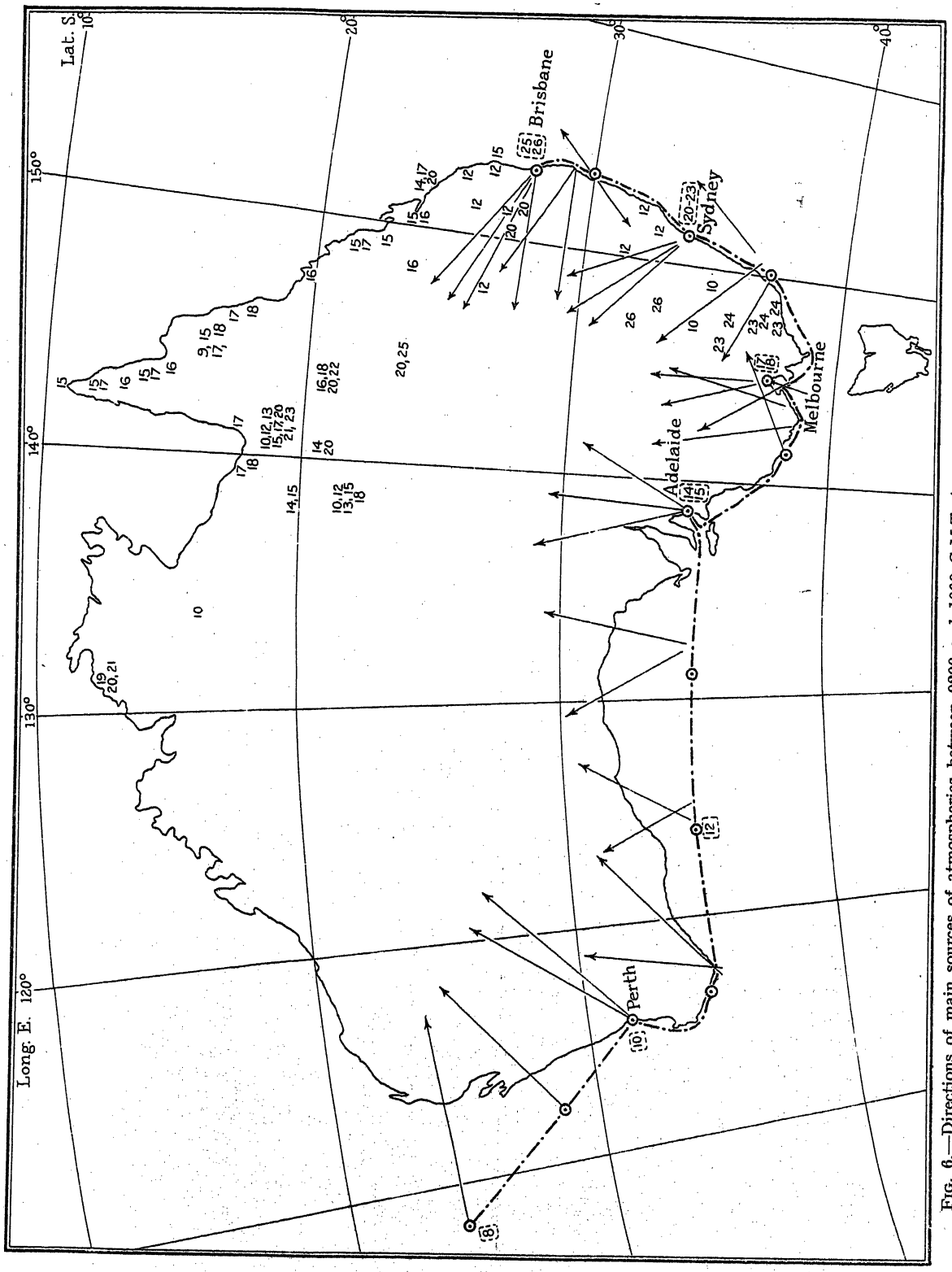


FIG. 6.—Directions of main sources of atmospherics between 0200 and 1000 G.M.T. (noon and 8 p.m. Melbourne time), January 1930.

NOTE.—Unenclosed numbers are dates of reported thunderstorms. Ship's position at local noon thus:—⊙; enclosed number [12] being the date.

December to the 2nd January very few atmospherics were observed between 110° and 180°. On the 3rd January, however, there is definitely another group at 140°, and on the 4th a further one at 50°. It appears that several sources are operating and it will be profitable to consider the diurnal variations.

In Fig. 5 are plotted all the observations taken during the period 3rd to 8th January inclusive, with the necessary corrections applied. The most noticeable feature is the progressive spreading of the distribution. In general the groups are too ill-defined to expect good intersections of directions, but it is nevertheless useful to study the isobronts for the area to the east. Brooks shows two very active thunderstorm areas, one just south of the Malay Peninsular and one in the north of Australia, while the whole archipelago between Australia and Asia is a region of frequent thunderstorms. The direction of the early morning group noted for the period 26th to 31st December passes through both the most active areas. It will be seen from Fig. 4 that there is a group each day at approximately 90°, which is especially marked in the later part of the day so that it probably is still largely due to the African source. From the 3rd to the 8th there is a progression of directions of recorded atmospherics from 90° towards 0°, consistent with the presence of an active region in the Malay area mentioned above, as is also the greater activity in the earlier hours. On the 7th and 8th, atmospherics are recorded between 0° and 30° for the first time in any number since the 26th December. They are also, from the 3rd to the 8th, recorded from various directions between 90° and 180°, suggesting scattered sources over the various islands and Australia.

Around the coast of Australia the distribution of the directions of sources changed considerably from day to day. The atmospherics were most intense and frequent during the local afternoon and evening, with directions and intensities such as to suggest that most of the sources were inland, particularly in the northern part of the Continent. In Fig. 6 the mean directions of the most active groups have been drawn in for all observations taken between 0200 and 1000 G.M.T. (noon and 8 p.m. Eastern States time), this period being chosen as being likely to restrict the observations mainly to atmospherics occurring over or near the Continent. By the courtesy of the Commonwealth Meteorological Bureau it has been possible to consider the results in conjunction with the meteorological records for the period, and it was found that in nearly all cases the directions of the main sources passed through areas of low barometric pressure in the north of the Continent, which generally had reported thunderstorms associated with them. This is especially marked from the 12th to the 26th January, when low pressures persisted over Central and Western Queensland and numerous thunderstorms were reported during the period. These are shown in Fig. 6, the dates on which thunderstorms or lightning were reported being marked in the position of the station reporting them. It will be seen that these are obviously dominating the supply of atmospherics. It was noted also that the intensity of the individual atmospherics was greatest in the Brisbane observations.

The Meteorological Bureau also kindly made available a series of records of atmospheric interference recorded hourly at a number of coastal wireless stations working on 600 metres. When compared with the directional observations for the corresponding times these confirmed the inland location of the sources, and it was evident that the thunderstorms caused serious interference with reception by day only when they were within 500 miles of the station.

Some night observations were also taken round the coast but they were not sufficient to warrant systematic analysis. They confirm, however, the earlier observations regarding the distant sources, for even at these distances the African source is quite appreciable at night.

Although the short period covered by these observations somewhat limits their value, they definitely support the theory of the thunderstorm origin for atmospherics. They also give an indication of the extent to which the supply of atmospherics in Australia would be dominated by local production, information which is useful in considering the establishment of more permanent observing stations. It may be mentioned that subsequent observations have confirmed the deductions which were made from these observations.

In the foregoing no distinction has been made between types of atmospherics such as " clicks " and " grinders," as is generally done in considering aural observations. The cathode-ray direction-finder shows clearly that the distinction is not one of fundamental types but merely of size and number, as increase of sensitivity will resolve the " grinders " into a great number of individuals of the " click " type. On this instrument, therefore, the size and frequency of occurrence are the best indications of the activity of sources. For the more distant and therefore weaker sources a greater area will be included in a given arc of azimuths, and the frequency of occurrence will naturally be greater than for close sources.

Acknowledgments.

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A NOTE ON THE THEORY OF NIGHT ERRORS IN ADCOCK DIRECTION-FINDING SYSTEMS.*

By J. F. COALES, B.A.

(*Paper first received* 16*th December*, 1931, *and in final form* 10*th March*, 1932.)

SUMMARY.

The paper deals with the theory of night errors (i.e. those errors which cannot be estimated owing to their variation from minute to minute and their dependence on factors not easily determined) in wireless direction-finding systems, and has arisen out of experimental work carried out at H.M. Signal School, Portsmouth.

Expressions are described for the errors which may be obtained as a result of the presence of both ground and atmospheric waves.

The fixed Adcock system is shown to be less liable to error than loop systems, but there are substantial zones in which, for certain conditions of the atmospheric or indirect ray from a transmitter, the fixed Adcock system is subject to blurred minima and to errors of bearing. These zones increase with increase of spacing between the aerials, and the maximum error occurs when the intensities of the ground and atmospheric waves are approximately equal. The rotating Adcock system, however, is shown to be free from blurred minima and errors due to night effect.

INTRODUCTION.

The problem considered in this paper is that of reception on two spaced vertical aerials situated above a perfect conductor, when the received energy is in part derived from the ground wave and in part from the atmospheric wave reflected from the Heaviside layer. The result is applied to Adcock direction-finding systems.

(1) CALCULATION OF THE ELECTRIC AND MAGNETIC FIELDS AT A POINT DISTANT h ABOVE THE SEA IN THE PRESENCE OF BOTH GROUND AND ATMOSPHERIC WAVES.

In Fig. 1, let OX represent the surface of the sea, which we will consider to be a perfect reflector.

Let AB be the wave-front of the downcoming wave (wavelength $= \lambda$) which, owing to the great distance traversed, we will consider to be plane.

Let P be a point at height h above the point O on the surface OX of the sea, and consider the atmospheric wave arriving at O to consist of two components, one polarized perpendicular to the plane of incidence AP'P and represented by an electric intensity $E_1 \sin\left[\omega t + (2\pi D_1/\lambda)\right]$ and a corresponding magnetic intensity $H_1 \sin\left[\omega t + (2\pi D_1/\lambda)\right]$, and the other polarized in the plane of incidence, the electric intensity of which is represented by $E_2 \sin\left[\omega t + (2\pi D_2/\lambda)\right]$ with corresponding magnetic intensity $H_2 \sin\left[\omega t + (2\pi D_2/\lambda)\right]$, where D_1 and D_2 are the optical paths measured to O of the two components respectively, and are in general different.

At P we have a difference of phase ϕ between the direct and reflected rays, where

$$\phi = \frac{2\pi}{\lambda}(\mathrm{AP'} + \mathrm{P'P} - \mathrm{BP}) = \frac{2\pi}{\lambda} 2h \cos\theta$$

Since we consider the reflector to be a perfect conductor, at the surface OX there can be no electric intensity parallel to that surface and we therefore find that, on reflection, the direction of E_1 is as shown in Fig. 1.

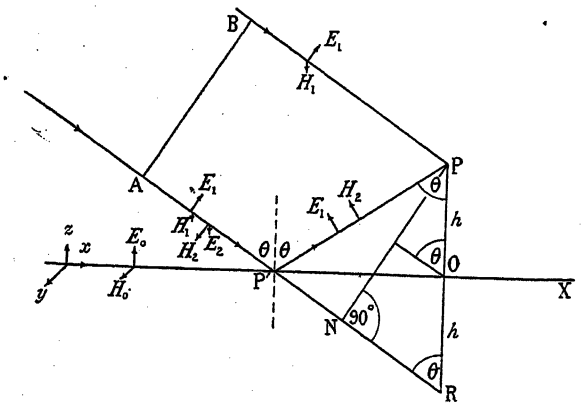


FIG. 1.

We therefore get at P

$$E_z = E_1 \sin\theta \sin\left(\omega t + \frac{2\pi D_1}{\lambda} - \frac{2\pi}{\lambda} h\cos\theta\right) + E_1 \sin\theta \sin\left(\omega t + \frac{2\pi D_1}{\lambda} + \frac{2\pi}{\lambda} h\cos\theta\right)$$

$$= 2E_1 \sin\theta \cos\left(\frac{2\pi h}{\lambda}\cos\theta\right) \sin\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

The component polarized in the plane of incidence can give no contribution to E_z and therefore if, in addition to the atmospheric wave, we have a ground wave which at O has intensities given by

$$E_x = 0, \quad E_y = 0, \quad E_z = E_0 \sin\left(\omega t + \frac{2\pi D_0}{\lambda}\right)$$

$$H_x = 0, \quad H_y = H_0 \sin\left(\omega t + \frac{2\pi D_0}{\lambda}\right), \quad H_z = 0$$

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the vertical electric field at the point P will be

$$E_z = E_0 \sin\left(\omega t + \frac{2\pi D_0}{\lambda}\right) + 2E_1 \sin\theta \cos\left(\frac{2\pi}{\lambda} h \cos\theta\right) \sin\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

Similar expressions may be obtained for the other components of the electric and magnetic fields at P in terms of E_1, E_2, H_1, H_2, etc.

We see from these that at any height above O the phase of any component of the fields is the same as that at O. If the wave were not perfectly reflected from the sea this would not necessarily be the case.

(2) The Vertical Electric Field at a Point P not Vertically above O.

Now consider two vertical aerials AB and CD, height H, distance D apart, and placed such that AC makes an angle ϕ with the direction of incidence of the ground wave (see Fig. 2).

From the equations above we have seen that the electric intensity at P′ due to the atmospheric wave is

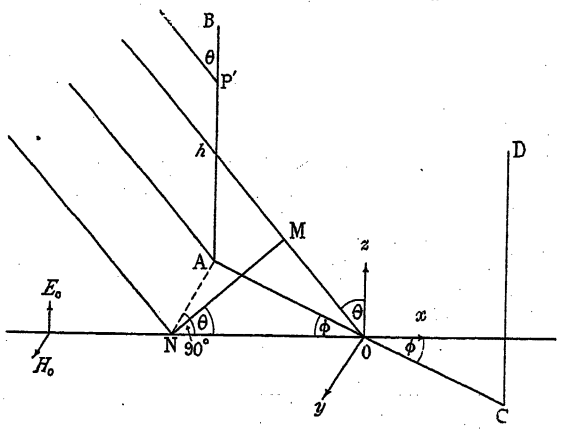


Fig. 2.

in phase with that at A, which is also in phase with that at N, AN drawn perpendicular to ON.

Now the difference in path between the ray at O and that at N is

$$\mathrm{OM} = \mathrm{ON} \sin\theta = \tfrac{1}{2} D \cos\phi \sin\theta$$

Thus at P′ we have

$$E_z = E_0 \sin\left(\omega t + \frac{2\pi D_0}{\lambda} - \frac{2\pi}{\lambda} \cdot \frac{D}{2} \cos\phi\right) + 2E_1 \sin\theta \cos\frac{(2\pi h \cos\theta)}{\lambda} \sin\left(\omega t + \frac{2\pi D_1}{\lambda} - \frac{2\pi}{\lambda} \cdot \frac{D}{2} \cos\phi \sin\theta\right)$$

(3) Application to the Rotating Adcock System.

In the perfect Adcock system we have the aerials so arranged (see Fig. 3) that the e.m.f.'s produced in the horizontal portions are equal and opposite and so have no effect.

We are concerned with the current through the coil L, i.e. the current in the aerial system. Now the current due to the potential at any height h may not be the same function of E_h for all values of h and so we must write

$$I = \left[\int_0^H f(h) E_h dh\right]_{AB} - \left[\int_0^H f(h) E_h dh\right]_{CD}$$

$$\therefore I = \int_0^H f(h) dh E_0 \left\{\sin\left(\omega t + \frac{2\pi D_0}{\lambda} + \frac{\pi D}{\lambda}\cos\phi\right) - \sin\left(\omega t + \frac{2\pi D_0}{\lambda} - \frac{\pi D}{\lambda}\cos\phi\right)\right\} + 2E_1 \sin\theta \int_0^H f(h) \cos\left(\frac{2\pi h}{\lambda}\cos\phi\right) dh \left\{\sin\left(\omega t + \frac{2\pi D_1}{\lambda} + \frac{\pi D}{\lambda}\sin\theta\cos\phi\right) - \sin\left(\omega t + \frac{2\pi D_1}{\lambda} - \frac{\pi D}{\lambda}\sin\theta\cos\phi\right)\right\}$$

$$= 2E_0 \int_0^H f(h) dh \sin\left(\frac{\pi D}{\lambda}\cos\phi\right) \cos\left(\omega t + \frac{2\pi D_0}{\lambda}\right) + 4E_1 \sin\theta \int_0^H f(h) \cos\left(\frac{2\pi}{\lambda} h \cos\theta\right) dh \times \sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right) \cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

In the above we have not taken into account the difference of phase of the current and e.m.f. in the

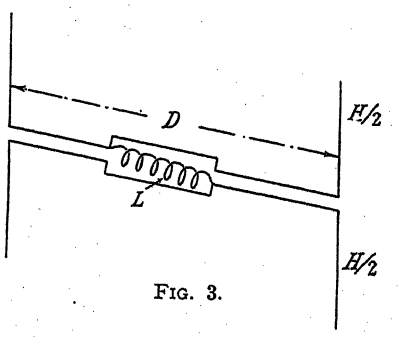


Fig. 3.

system; this will not affect the form of the expression, but only the position of the origin of t.

We see from this expression that whatever the magnitude and phases of E_0 and E_1 when $\phi = \frac{1}{2}\pi$, then $I = 0$, and so in the rotating Adcock system over the sea no error or blurring of the minimum arises purely from the presence of atmospheric wave as well as ground wave.

(4) Application to the Fixed Adcock Direction-Finding System.

In the fixed Adcock system, however, we have two aerial systems, A and B (represented by AC and A′C′ in Fig. 4A), which are set at right angles to each other, so that if ϕ is the angle which the direction of incidence of the wave makes with system A we have for the currents in the coils L_A and L_B

$$I_A = E_0 \sin\left(\frac{\pi D}{\lambda}\cos\phi\right) \cos\left(\omega t + \frac{2\pi D_0}{\lambda}\right) + E_A \sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right) \cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

$$I_B = E_G \sin\left(\frac{\pi D}{\lambda}\sin\phi\right)\cos\left(\omega t + \frac{2\pi D_0}{\lambda}\right) + E_A \sin\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right)\cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

putting $$E_G = 2E_0\int_0^H f(h)dh$$

$$E_A = 4E_1 \sin\theta \int_0^H f(h)\cos(2\pi h\cos\theta)dh$$

Now if L_A and L_B are the fixed coils of a goniometer, the e.m.f. induced in the search coil when the angle of coupling is ψ will be E, where

$$kE = I_B\cos\psi - I_A\sin\psi \quad \text{(see Fig. 4B)}$$

since the e.m.f. induced in the coil is proportional to the total flux through it, which is the sum of the resolved

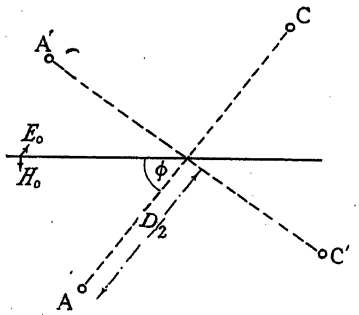


FIG. 4A.—Plan showing distribution of aerials in the fixed Adcock direction-finding system.

fluxes due to the two fixed coils, which fluxes are proportional to I_A and I_B.

$$\therefore\ kE = E_G\left\{\cos\psi\sin\left(\frac{\pi D}{\lambda}\sin\phi\right) - \sin\psi\sin\left(\frac{\pi D}{\lambda}\cos\phi\right)\right\}\cos\left(\omega t + \frac{2\pi D_0}{\lambda}\right) + E_A\left\{\cos\psi\sin\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right) - \sin\psi\sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right)\right\}\cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right)$$

where k is a constant, and ψ will be the observed relative bearing when E is a minimum, which will in general be when $\psi \neq \phi$, the true relative bearing.

From this we see that E corresponds to that due to a rotating field in the goniometer; in general there is no value of ψ which makes E zero, and so there is possibility of blurring of the minima and of errors in the observed bearing.

(5) MAGNITUDE OF ERRORS IN OBSERVED BEARINGS.

The expression for E obtained above may be simplified to give $kE = A\sin(\omega t + B)$, where A and B are both functions of ψ.

Now if ϵ is the difference between $\psi_{min.}$ the observed bearing in the presence of both ground and atmospheric waves, and ψ_1 the observed bearing in the presence of ground wave alone (ψ_1 in general differs from ϕ, but this difference is constant and known for any value of ψ and is given by a calibration curve), it can be shown that

$$A^2 = \beta + \gamma\cos 2\epsilon + \delta\sin 2\epsilon$$

where

$$2\beta = a_1^2E_G^2 + a_2^2E_A^2 + 2a_1a_2E_GE_A\cos(\psi_1 - \psi_2)\cos\frac{2\pi d_1}{\lambda}$$

$$-2\gamma = a_1^2E_G^2 + a_2^2E_A^2\cos 2(\psi_1 - \psi_2) + 2a_1a_2E_GE_A\cos(\psi_1 - \psi_2)\cos\frac{2\pi d_1}{\lambda}$$

$$\delta = a_2E_A\sin(\psi_1 - \psi_2)\left\{a_1E_G\cos\frac{2\pi d_1}{\lambda} + a_2E_A\cos(\psi_1 - \psi_2)\right\}$$

In these expressions

$$d_1 = D_1 - D_0,$$

or $2\pi d_1/\lambda$ = difference in phase between atmospheric wave and ground wave.

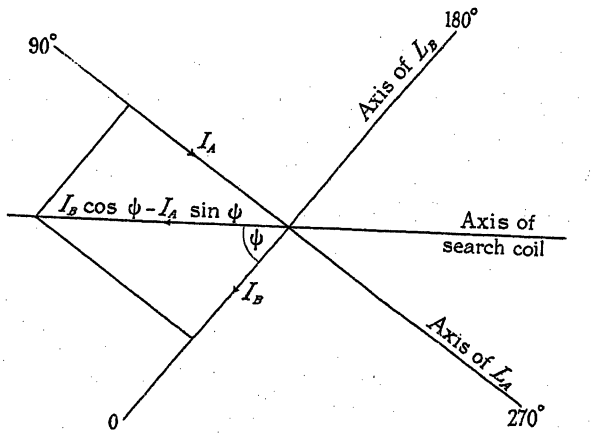


FIG. 4B.

The aerials are connected to the goniometer in such a way that the directions of the fields due to I_A and I_B are as shown. The cardinal points on the scale are also inserted.

ψ_1 is the observed bearing in the presence of the ground wave alone, given by

$$\tan\psi_1 = \frac{\sin[(\pi D/\lambda)\sin\phi]}{\sin[(\pi D/\lambda)\cos\phi]}.$$

ψ_2 is the observed bearing in the presence of atmospheric wave alone [$(\psi_2 - \phi)$ similarly to $(\psi_1 - \phi)$ could be evaluated, provided θ were known, which is not usually the case], given by

$$\tan\psi_2 = \frac{\sin[(\pi D/\lambda)\sin\phi\sin\theta)]}{\sin[(\pi D/\lambda)\cos\phi\sin\theta]}$$

$$a_1^2 = \sin^2\left(\frac{\pi D}{\lambda}\sin\phi\right) + \sin^2\left(\frac{\pi D}{\lambda}\cos\phi\right)$$

$$a_2^2 = \sin^2\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right) + \sin^2\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right)$$

From this expression for A^2, by differentiation with respect to ϵ we find that the signal strength, which is proportional to A, has stationary values when

$$\tan 2\epsilon = \frac{\delta}{\gamma}$$

that is when

$$A^2_{min.} = \beta + \gamma = a_2^2E_A^2 \sin^2(\psi_1 - \psi_2)$$

$$A^2_{max.} = \beta - \gamma = a_2^2E_2^2 \cos^2(\psi_1 - \psi_2) + a_1^2E_G^2 + 2a_1a_2E_GE_A \cos(\psi_1 - \psi_2) \times \cos(2\pi d_1/\lambda)$$

$$= a_1^2E_G^2 - a_2^2E_A^2 \cos^2(\psi_1 - \psi_2)$$

$$\therefore A^2_{max.} - A^2_{min.} = a_1^2E_G^2 - a_2^2E_A^2$$

$$\tan 2\epsilon = -\frac{2a_2E_A \sin(\psi_1 - \psi_2)\{a_1E_G \cos(2\pi d_1/\lambda) + a_2E_A \cos(\psi_1 - \psi_2)\}}{a_1^2E_G^2 + a_2^2E_A^2 \cos 2(\psi_1 - \psi_2) + 2a_1a_2E_GE_A \cos(\psi_1 - \psi_2)\cos(2\pi d_1/\lambda)}$$

From this expression we see that the error ϵ of the observed bearing varies with the difference of phase of the two waves, being a maximum when $2\pi d_1/\lambda = (2n+1)\pi$ and a minimum when $2\pi d_1/\lambda = 2n\pi$. The way in which ϵ varies with $2\pi d_1/\lambda$ for any particular values of $a_2E_A/(a_1E_G)$ and $\psi_1 - \psi_2$ is shown in Fig. 5, where ϵ is plotted against $2\pi d_1/\lambda$ when $a_2E_A/(a_1E_G) = 2$ and when $\psi_1 - \psi_2 = 3'\,45°$, corresponding to

$$D = 0{\cdot}5, \quad \phi = 25°, \quad \theta = 45°$$

It should be noted that when the phase difference between the two waves is X, say, at O in Fig. 2, or any point up a vertical line at the centre of the system, it

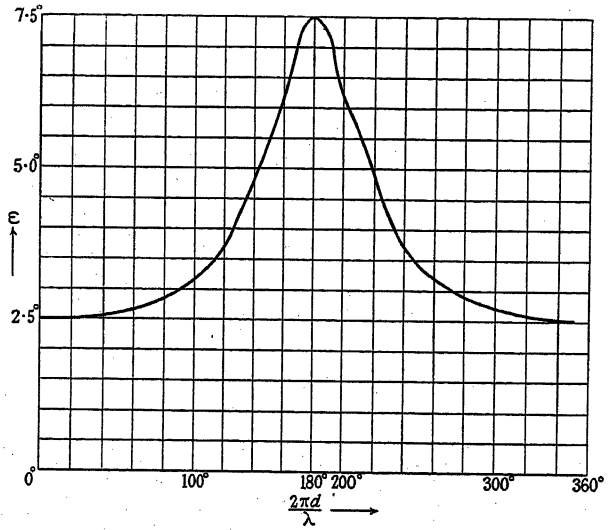


FIG. 5.—Variation of ε with $2\pi d/\lambda$ when $(a_2E_A)/(a_1E_G) = 2$, $D/\lambda = 0{\cdot}5$.

$\psi_1 - \psi_2 = 3°\,45'$.
$(\phi = 25°, \theta = 45°, D/\lambda = 0{\cdot}5.)$

is not X at any point on the aerials of the system; but is different for each aerial, the value depending on D, θ and ϕ.

(6) Possibility of a 90° Error and Conditions for which the Error does not Depend on d_1.

From the expression for $\tan 2\epsilon$ we get the following special cases:—

$\epsilon = 0$ or $\frac{1}{2}\pi$ when $a_2E_A \cos(\psi_1 - \psi_2) = -a_1E_G \cos(2\pi d_1/\lambda)$

Taking $\epsilon = 0$ we have $\sin 2\epsilon = 0$; $\cos 2\epsilon = 1$ and

Therefore if $a_1^2E_G^2 < a_2^2E_A^2$ we have $A^2_{max.} < A^2_{min.}$, so that the positions of maximum and minimum change places and we have $\epsilon = 90°$ when

$$a_2E_A > a_1E_G \quad \text{and} \quad a_2E_A \cos(\psi_1 - \psi_2) = -a_1E_G \cos(2\pi d_1/\lambda)$$

But the maximum value of the molulus of $\cos(2\pi d_1/\lambda)$ is 1, and so the maximum value of $a_2E_A/(a_1E_G)$ for which the equality is possible is $\sec(\psi_1 - \psi_2)$.

Thus when $a_2E_A/(a_1E_G)$ has a value lying between

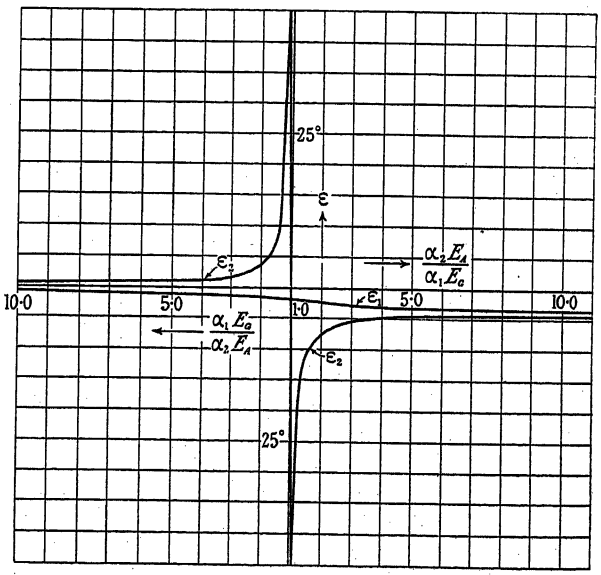


FIG. 6.—Variation of ε_1 and ε_2 with $(a_2E_A)/(a_1E_G)$ when $\psi_1 - \psi_2 = 3°\,45'$.

$(\phi = 25°, \theta = 45°; D/\lambda = 0{\cdot}5.)$

1 and $\sec(\psi_1 - \psi_2)$ [which is very nearly equal to 1 in practice since $(\psi_1 - \psi_2)$ is small $(< 10°)$], and when $-\cos(2\pi d_1/\lambda)$ lies between 1 and $\cos(\psi_1 - \psi_2)$ then there is a possibility of a 90° error.

In this case, of course, the minimum will be extremely flat, in fact it would probably be quite impossible to obtain any reading unless $(\psi_1 - \psi_2)$ were large.

ϵ is single-valued for all values of $2\pi d_1/\lambda$, only in three cases $a_2E_A = 0$, $a_2E_A = a_1E_G$ and $a_1E_G = 0$ when the corresponding values of ϵ are $\epsilon = 0$, $\epsilon = -\frac{1}{2}(\psi_1 - \psi_2)$, and $\epsilon = -(\psi_1 - \psi_2)$ respectively.

For all other values of $a_2E_A/(a_1E_G)$, ϵ varies with d_1 in the way shown in Fig. 5.

(7) VARIATION OF THE EXTREME VALUES OF THE ERROR WITH THE RATIO OF THE INTENSITIES OF THE WAVES.

In Figs. 6 and 7 and Table 1 is shown the way in which the limiting values of ϵ, corresponding to $\cos(2\pi d_1/\lambda) = 1$ and $\cos(2\pi d_1/\lambda) = -1$, called ϵ_1 and ϵ_2, vary with $\alpha_2 E_A/(\alpha_1 E_G)$ for different values of $(\psi_1 - \psi_2)$. In Fig. 6 the plot is for $(\psi_1 - \psi_2) = 3° 45'$, corresponding to $D/\lambda = 0{\cdot}5$, $\theta = 45°$, $\phi = 25°$ (see Fig. 2). This shows that ϵ_1 gradually increases from zero to $-(\psi_1 - \psi_2)$ as $\alpha_2 E_A/(\alpha_1 E_G)$ increases from 0 to ∞, while ϵ_2 rises to 45° at $\alpha_2 E_A/(\alpha_1 E_G) = 0{\cdot}94$, then drops to $-\frac{1}{2}(\psi_1 - \psi_2)$ at $\alpha_2 E_A/(\alpha_1 E_G) = 1{\cdot}0$ and decreases further to $-45°$ at $\alpha_2 E_A/(\alpha_1 E_G) = 1{\cdot}07$, and between $1{\cdot}0$ and $1{\cdot}07$ ϵ may, under certain conditions, take the value 90° as shown above. Thus we see that for that value of $(\psi_1 - \psi_2)$ the error must lie in the area defined by the curves for ϵ_1 and ϵ_2.

(8) VARIATION OF ϵ_1 AND ϵ_2, THE EXTREME VALUES OF THE ERROR, WITH THE DIMENSIONS OF THE SYSTEM AND WITH THE SITUATION OF THE TRANSMITTER.

The magnitude of the error for any given value of $\cos(2\pi d_1/\lambda)$ varies with $(\psi_1 - \psi_2)$, and in Fig. 7 ϵ_1 and ϵ_2, the limiting values, are plotted against $\alpha_2 E_A/(\alpha_1 E_G)$ for three values of $(\psi_1 - \psi_2)$, viz. 0° 9′, 1° 9′, and 3° 45′.

From this we see that as $(\psi_1 - \psi_2)$ decreases, the curves recede towards the axes, the limiting values for any given value of $\alpha_2 E_A/(\alpha_1 E_G)$, not between those for which $\epsilon = \pm 45°$, decreasing with $(\psi_1 - \psi_2)$ (see Fig. 8), and as $(\psi_1 - \psi_2)$ decreases so the area in which errors greater than, say, 1° can occur decreases, since the limits of $\alpha_2 E_A/(\alpha_1 E_G)$, between which the error ϵ can be more than 1°, approach each other (see Fig. 9). Now $(\psi_1 - \psi_2)$ depends on ϕ, θ, and D/λ, and Table 2 shows the values $(\psi_1 - \psi_2)$ when $\phi = 25°$, $\theta = 45°$ for different values of D/λ.

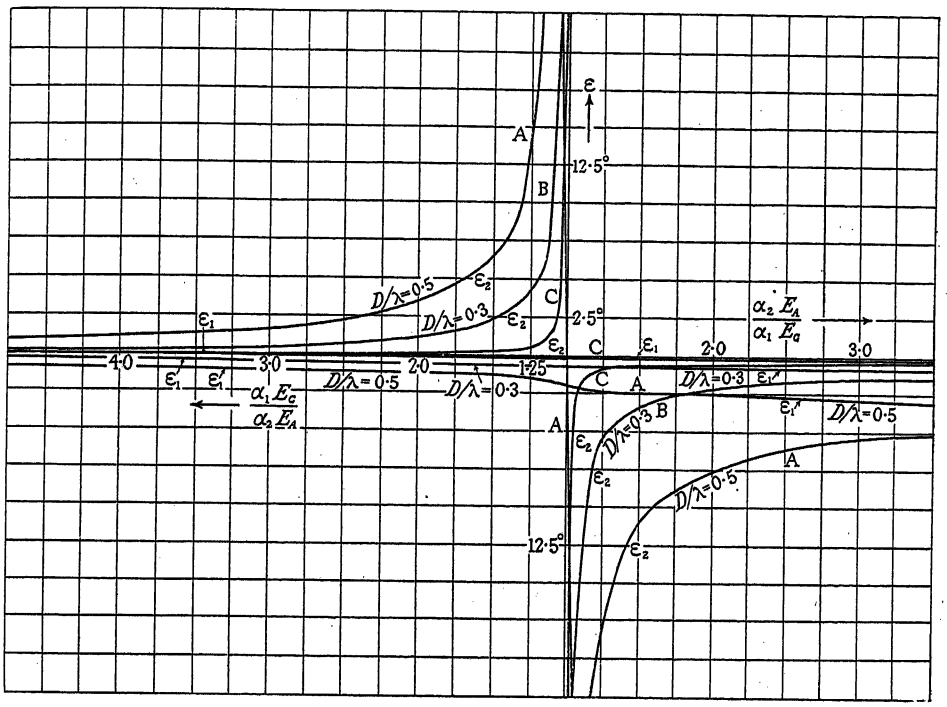


FIG. 7.—Variation of ϵ_1 and ϵ_2 with $(\alpha_2 E_A)/(\alpha_1 E_G)$.

Curve A.—When $\psi_1 - \psi_2 = 3° 45'$. ($\theta = 45°$; $\phi = 25°$; $D/\lambda = 0{\cdot}5$.)
Curve B.—When $\psi_1 - \psi_2 = 1° 9'$. ($\theta = 45°$; $\phi = 25°$; $D/\lambda = 0{\cdot}3$.)
Curve C.—When $\psi_1 - \psi_2 = 0° 9'$. ($\theta = 45°$; $\phi = 25°$; $D/\lambda = 0{\cdot}11$.)

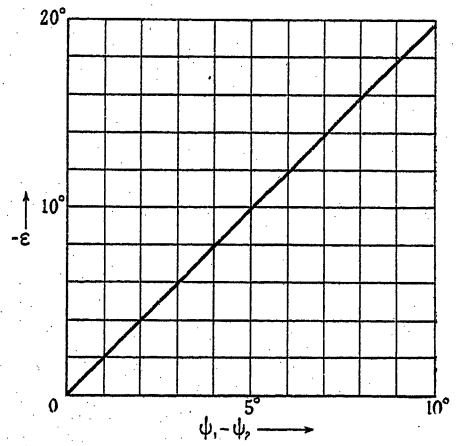


FIG. 8.—ϵ_2 plotted against $\psi_1 - \psi_2$.

Particular case:— $(\alpha_2 E_A)/(\alpha_1 E_G) = 2$; and $\cos(2\pi d/\lambda) = -1$.

In Table 1, where no value of ϵ is given it means that the change of ϵ is so small that it has been considered unnecessary to calculate the exact value, so no

TABLE 1.

$\frac{a_1E_G}{a_2E_A}$	$\frac{a_2E_A}{a_1E_G}$	$(\psi_1-\psi_2)=0°\ 9'$		$(\psi_1-\psi_2)=1°\ 9'$		$(\psi_1-\psi_2)=3°\ 45'$	
		ϵ_1	ϵ_2	ϵ_1	ϵ_2	ϵ_1	ϵ_2
—	0	0	0	0	0	0	0
10	0·1	− 1′	+ 1′	− 6′	+ 7½′	− 20½′	+ 25′
5	0·2	− 1½′	+ 2½′	− 11½′	+ 17½′	− 38′	+ 57′
4	0·25	—	—	—	—	− 45′	+ 1° 13′
3	0·33	—	—	—	—	− 56′	+ 1° 52′
2	0·5	− 3′	+ 9′	− 24′	+ 1° 12′	− 1° 15′	+ 3° 44′
1·5	0·67	—	—	− 27½′	+ 2° 18′	—	—
1·43	0·7	− 3½′	+ 21′	—	—	− 1° 33′	+ 8° 13′
1·25	0·8	− 4′	+ 36′	− 30½′	+ 4° 31′	− 1° 40′	+ 14° 40′
1·11	0·9	− 4½′	+ 1° 21′	− 34′	+ 9° 56′	− 1° 46′	+ 29° 55′
1·063	—	—	—	—	—	—	+ 45° 0
1·053	0·95	− 4½′	+ 2° 51′	—	+ 21° 28′	—	—
1·02	—	—	—	—	+ 45° 0′	—	—
1·01	0·99	—	—	—	+ 26° 32′	—	—
1·00	1·00	− 4½°	± 45°	− 35′	− 0° 35′	− 1° 52′	− 1° 52
—	1·002	—	—	—	—	− 1° 56′	0° 0′
—	1·02	—	—	—	− 45° 0′	—	—
—	1·05	—	—	—	− 26° 44′	—	—
—	1·06	—	—	—	− 22° 55′	—	—
—	1·072	—	—	—	—	—	—
—	1·10	− 4½′	− 1° 39′	− 36′	− 12° 21′	—	− 45° 0′
—	1·20	− 5′	− 54′	—	—	− 2° 2′	—
—	1·25	—	—	− 38½′	− 5° 41′	—	− 20° 36′
—	1·5	—	—	− 41½′	− 3° 25′	− 2° 15′	—
—	2·0	− 6′	− 18′	− 46′	− 2° 18′	− 2° 31′	− 11° 6′
—	3·0	—	—	—	—	− 2° 48′	− 7° 30′
—	4·0	− 7′	− 12′	—	—	− 2° 58′	− 5° 33′
—	5·0	—	—	− 1° 0′	− 1° 27′	− 3° 6′	− 4° 56′
—	7·0	—	—	—	—	− 3° 15′	− 4° 39′
—	10·0	− 8′	− 10′	− 1° 3′	− 1° 17′	− 3° 24′	− 4° 21′
0	—	− 9′	− 9′	− 1° 9′	− 1° 9′	− 3° 45′	− 4° 7′
							− 3° 45′

value has been inserted. The value, if required, may be obtained by interpolation.

TABLE 2.

$\frac{D}{\lambda}$	$(\psi_1-\psi_2)$
0·1	0° 7′
0·3	1° 9′
0·5	3° 45′

$(\psi_1-\psi_2)$ decreases from $(\psi_1-\phi)$ to zero as θ increases from 0 to $\frac{1}{2}\pi$, and is always zero when $\phi = 0°$, 45°, 90°, 135°, 180°, etc., and has its maximum value at $\phi = 22\frac{1}{2}°$, $67\frac{1}{2}°$, etc.

In Table 3 are given the values of the various quantities on which the limiting values of the error depend, for different distances from a transmitter, for which $D/\lambda = 0{\cdot}1$, and for $\phi = 25°$, assuming the height of the Heaviside layer to be 100 kilometres.

Values for the field intensities of the direct and indirect waves at various distances oversea from a transmitter estimated from some measurements taken with the Orfordness beacon have been used and it has been assumed that at any distance from the transmitter

$$\frac{E_A}{E_A} = \frac{2E\ \text{(indirect wave)}}{E\ \text{(direct wave)}}$$

which is only approximate in the receiving case unless the height of the aerials is small.

The values have been worked out, assuming the downcoming wave to be entirely polarized perpendicular to the plane of incidence, which means that the value of E_A/E_G used is probably too large, which would require that in the curves drawn against distance, Figs. 9 and 10, and in the diagram, Fig. 11, the distance scale should be increased so that instead of a limiting error of 1° occurring at 280 km it should occur at 600 km, say.

The way in which the errors are computed for any distance is as follows.

First E_A/E_G is calculated from the estimated values of the intensities, and θ is calculated by direct triangu-

TABLE 3.

ϵ_2 Calculated for Different Distances from Transmitter.

Distance from transmitter	$\frac{E_A}{E_G}$	θ	$D/\lambda = 0{\cdot}1$; $\phi = 25°$: $\frac{\pi D}{\lambda}\sin\phi\sin\theta$	$\frac{\pi D}{\lambda}\cos\phi\sin\theta$	α_1	α_2	ψ_1	ψ_2	$(\psi_1-\psi_2)$	$\frac{\alpha_2 E_A}{\alpha_1 E_G}$	$(\psi_1-\psi_2=9')$	ϵ_2
km												
100	0·42	26½°	3°·39	7°·27	0·31	0·140	25° 15′	25° 3½′	11½′	0·19	2½′	3½′
150	0·61	37°	4°·58	9°·81	0·31	0·188	—	—	9′	0·37	10′	10′
200	0·79	45°	5°·38	11°·53	0·31	0·221	25° 15′	25° 8′	7½′	0·56	15′	12′
250	0·93	51°	5°·91	12°·67	0·31	0·242	—	—	6½′	0·73	25′	17′
275	1·11	53½°	—	—	0·31	0·251	—	—	5¾′	0·90	1° 20′	51′
300	1·20	56°	6°·30	13°·51	0·31	0·259	25° 15′	25° 9½′	5½′	1·0	—	45°
325	1·29	58°	—	—	0·31	0·264	—	—	4¾′	1·10	−1° 36′	−51′
350	1·44	60°	6°·58	14°·11	0·31	0·269	25° 15′	25° 11′	4½′	1·25	−45′	−20′
400	1·75	63½°	6°·81	14°·59	0·31	0·277	25° 15′	25° 12′	4′	1·56	−30′	−10′
450	2·10	66°	6°·95	14°·90	0·31	0·284	—	—	3½′	1·92	−18′	−6′
500	2·50	68°	7°·05	15°·11	0·31	0·288	—	—	3′	2·33	—	—
600	3·25	71½°	7°·21	15°·45	0·31	0·294	—	—	2′	3·07	—	—
650	3·70	73°	7°·27	15°·59	0·31	0·297	—	—	—	3·55	—	—
700	4·15	74°	7°·31	15°·66	0·31	0·298	—	—	1½′	4·00	−12′	−4′
800	7·00	76°	7°·38	15°·81	0·31	0·301	25° 15′	25° 12′	1½′	6·80	−11′	−3⅔′
			$D/\lambda = 0{\cdot}1$; $\phi = 15°$									
350	1·44	60°	4°·04	15°·06	0·314	0·269	15° 12′	15° 8′	4′	1·25	−45′	20′

lation. Then $(\pi D/\lambda)\sin\phi$, $(\pi D/\lambda)\cos\phi$, $(\pi D/\lambda)\sin\phi\sin\theta$, and $(\pi D/\lambda)\cos\phi\sin\theta$ are calculated for the values of D/λ and ϕ considered, and from these are obtained

$$\alpha_1 = \left\{\sin^2\left(\frac{\pi D}{\lambda}\sin\phi\right) + \sin^2\left(\frac{\pi D}{\lambda}\cos\phi\right)\right\}^{\frac{1}{2}}$$

$$\alpha_2 = \left\{\sin^2\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right) + \sin^2\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right)\right\}^{\frac{1}{2}}$$

$$\psi_1 = \arctan\frac{\sin\left[(\pi D/\lambda)\sin\phi\right]}{\sin\left[(\pi D/\lambda)\cos\phi\right]}$$

$$\psi_2 = \arctan\frac{\sin\left[(\pi D/\lambda)\sin\phi\sin\theta\right]}{\sin\left[(\pi D/\lambda)\cos\phi\sin\theta\right]}$$

Having the values of these quantities, $\alpha_2 E_A/(\alpha_1 E_G)$ and $(\psi_1 - \psi_2)$ are then obtained, and then from Fig. 7 the values of ϵ_1 and ϵ_2 can be obtained for a certain value of $(\psi_1 - \psi_2)$, say 9′. Then the ratio of the value of ϵ for $(\psi_1 - \psi_2) = 9'$ to that value of ϵ for the actual $(\psi_1 - \psi_2)$ can be taken from Fig. 8, and so the actual values of ϵ_1 and ϵ_2 can be obtained for the given conditions.

In Fig. 10 is shown the plot of the modulus of ϵ_2 against the distance from the transmitter in kilometres when the height of the Heaviside layer is 100 km.

The values of the various quantities in Table 3 were also calculated for $\phi = 15°$ at a distance of 300 km and found to be almost exactly the same as for $\phi = 25°$. From these values and the fact that the error is zero when $\phi = 0$, 45°, 90°, etc., the shape of the areas was surmised to be roughly that shown in Fig. 11, which was drawn to show the areas within which the modulus of the limiting value of the error ϵ_2 is greater than 1° for a transmitter (see below) or receiver with aerials

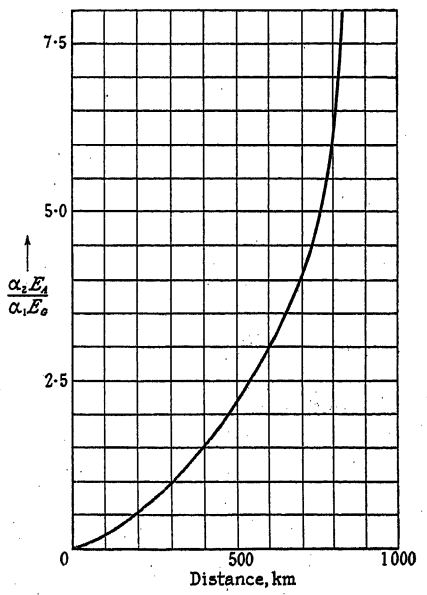


FIG. 9.—$(\alpha_2 E_A)/(\alpha_1 E_G)$ plotted against the distance (km) from the transmitter.

$\phi = 25°$; height of Heaviside layer = 100 km.

spaced $\lambda/10$ apart. In Fig. 11 is also shown the boundary (full line) of the area within which $\epsilon_2 > \frac{1}{2}°$.

It should be noted that these values of the limiting errors are worked out for a particular height of the Heaviside layer, and as this height varies so θ varies

and so the areas shown will move inwards or outwards and alter in size to some extent. The movement of the

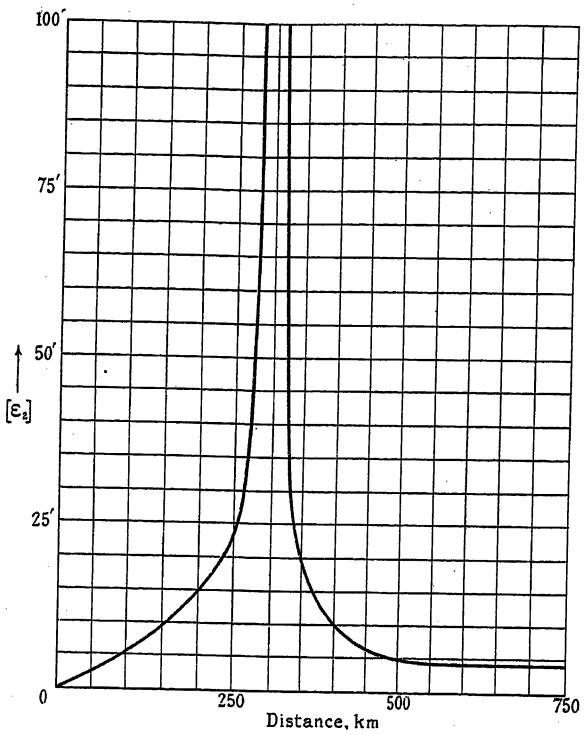


FIG. 10.—Modulus of ε_2 (the maximum possible error of the observed bearing) plotted against the distance (km) from the transmitter, when $D/\lambda = 0{\cdot}1$.

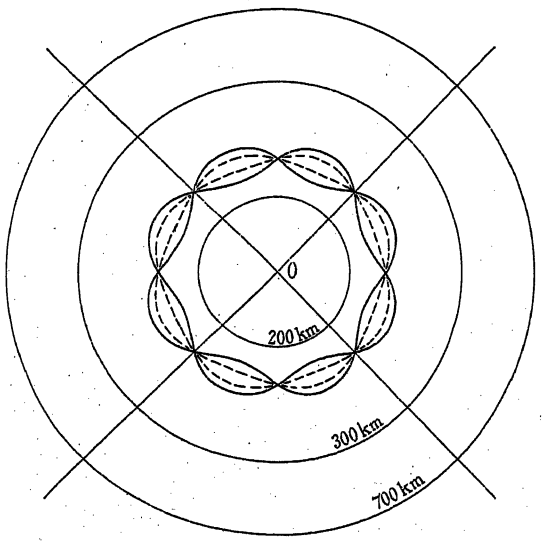


FIG. 11.—Diagram showing areas in which the error ε of the observed bearing may be $> \frac{1}{2}°$ for $D/\lambda = 0{\cdot}1$.

In area between full and dotted lines ϵ may lie between $\frac{1}{2}°$ and 1°. Inside dotted line ϵ may be 1° at any place and in centre be as much as 45°. The transmitter is situated at 0.
If $D/\lambda = 0{\cdot}3$ the boundaries would correspond to about 5° and 8° instead of $\frac{1}{2}°$ and 1°.

aviside layer will of course greatly affect d_1, and so error will vary from minute to minute, and will only sionally have the value ϵ_2.

Thus it is seen that, using a fixed Adcock system, there are considerable areas, a few hundred kilometres from the transmitter, in which when $D/\lambda = 0{\cdot}1$ the error of the observed bearing may be more than 1°, and may in certain places be 20° or more, while for $D/\lambda = 0{\cdot}3$ anywhere in these areas the error may be as much as 5° and in some places 20° or more.

The ratio of the squares of the amplitudes in the maximum and minimum positions has been calculated for different conditions and it has been found that until the error becomes greater than 1° this ratio is never less than 500, so that blurring of the minimum is not serious until errors of several degrees occur.

(9) Relation between Errors and "Fading."

It is seen from the expression for the error caused by the downcoming wave that the maximum error always occurs when $2\pi d_1/\lambda = \pi$, i.e. when the vertical component of the electrical field due to the atmospheric wave is opposite in phase to that due to the ground wave, and so "fading" is at its worst and the signal received weak. In Table 4 are given approximate

TABLE 4.

Distance from transmitter	$\frac{E_z}{E_G}$ (ground wave alone)	Approximate error ϵ_2 when $\frac{2\pi d_1}{\lambda} = \pi$		
		$\frac{D}{\lambda} = 0{\cdot}1$	$\frac{D}{\lambda} = 0{\cdot}3$	$\frac{D}{\lambda} = 0{\cdot}5$
miles				
150	0·63	10′	0°·75	1°·75
200	0·44	12′	1°·0	2°·25
250	0·28	17′	2°·25	6°·5
275	0·11	51′	5°·75	20°
300	very small indeed	45°	45°	45°
325	−0·10	−51′	−6°·1	−19°·5
350	−0·24	−20′	−2°·35	−7°·7
400	−0·56	−10′	−1°·5	−5°

values for the amplitudes of the resultant field, in terms of that in the presence of ground wave alone, for distances from the transmitter near that at which the error may be 45°, corresponding approximate values for the error ϵ_2 when $D/\lambda = 0{\cdot}1$, $D/\lambda = 0{\cdot}3$, and $D/\lambda = 0{\cdot}5$ being given in columns 3 to 5. If there is no fading, the signal strength being equal to that in the presence of ground wave alone, then the value of $2\pi d_1/\lambda$ must be $\frac{1}{2}\pi$ or $\frac{3}{2}\pi$, and so we find that the expression for the error ϵ is given by

$$\tan 2\epsilon = -\frac{\sin 2(\psi_1 - \psi_2)}{\alpha_1^2 E_G^2/(\alpha_2^2 E_A^2) + \cos 2(\psi_1 - \psi_2)}$$

$\alpha_1^2 E_G^2/(\alpha_2^2 E_A^2)$ must always be positive and $(\psi_1 - \psi_2)$ is always small when $D/\lambda < 0{\cdot}5$, and so we find that the error ϵ is always less than $(\psi_1 - \psi_2)$, and, when near the places of large error for $2\pi d_1/\lambda = \pi$, $\alpha_1 E_G/(\alpha_2 E_A)$ is approximately unity and so $\epsilon = \frac{1}{2}(\psi_1 - \psi_2)$ approximately. Values of $(\psi_1 - \psi_2)$ for different values of θ and D/λ are given in Table 5.

It is thus seen that large errors in the observed direction-finder bearing are always accompanied by "severe fading" so that the signal strength received is weak. The greater the spacing of the aerial system the less complete the fading.

(10) Errors in the Absence of a Ground Wave.

When only the atmospheric wave is present the observed bearing is ψ_2, given by

$$\tan \psi_2 = \frac{\sin [(\pi D/\lambda) \sin \phi \sin \theta]}{\sin [(\pi D/\lambda) \cos \phi \sin \theta]}$$

and so varies with θ, the angle which the downcoming wave makes with the vertical.

There is, as we have seen, always a correction $\psi_1 - \phi$ to be applied, so that the only variable error is $(\psi_1 - \psi_2)$. ψ_1 is greatest when $\phi = 22\frac{1}{2}°$, and $\psi_2 - \psi_1$ will also be greatest for this value. Unless we know the value of θ it is impossible to estimate this error $(\psi_1 - \psi_2)$ which therefore comes in the category of indeterminate errors, with all others due to "night effect." The values of $(\psi_1 - \psi_2)$ for different values of θ and D/λ are given in Table 5 and it is seen that these errors are only considerable when $D/\lambda > 0{\cdot}1$.

Table 5.

Value of $(\psi_1 - \psi_2)$, the Error of the Observed Bearing from the Calibration Curve, for Different Values of θ, the Angle of Incidence of the Atmospheric Wave, when there is no Ground Wave present, ϕ, the Relative Bearing of the Transmitter, being $22\frac{1}{2}°$.

θ	$(\psi_1 - \psi_2)$ when $D/\lambda = 0{\cdot}1$	$(\psi_1 - \psi_2)$ when $D/\lambda = 0{\cdot}3$	$(\psi_1 - \psi_2)$ when $D/\lambda = 0{\cdot}5$
0°*	0° 14½′	2° 16′	7° 10′
10°	0° 14½′	2° 7′	7° 0½′
20°	0° 13′	2° 1′	6° 39′
30°	0° 10½′	1° 44′	5° 37′
40°	0° 8½′	1° 22′	4° 32′
50°	0° 6½′	0° 58′	3° 18′
60°	0° 4½′	0° 36′	2° 3′
70°	0° 2′	0° 17′	0° 59½′
80°	0° ½′	0° 4′	0° 16′
90°	0° 0′	0° 0′	0° 0′

* When the angle of incidence is 0 there is, of course, no pick-up; this is only a limiting value given here.

(11) Application to the Fixed Adcock Transmitting System.

Let the angle of coupling of the goniometer in a fixed Adcock transmitting beacon be ψ, and let the direction of the observer make angle ϕ with the plane of one pair of aerials.

The current in one pair is then $kI \sin \psi$ and in the other pair $kI \cos \psi$

The phase of the e.m.f. at any part of the transmitting aerial must be the same all up the aerial, but E_h, the potential at any point, will be a function of h so we have

$$E_h = kIf(h) \sin \psi \sin \omega$$

at any moment.

At a distant point we shall have exactly the same path differences for the two components of the ground ray as for the path differences of the two components received in the two halves of the aerial in the receiving case. Similarly for the atmospheric rays, both the direct and that reflected from the ground, the path differences will be the same. Owing, however, to effects which depend on the direction of propagation, it may be that the ratio (atmospheric intensity)/(ground intensity) may not be the same in the two cases, but this does not affect the possibility of these large errors and blurred minima unless there can never be a component of the downcoming ray, polarized perpendicular to the plane of incidence great enough for $\alpha_2 E_A/(\alpha_1 E_G) = 1$ (approx.), or, if there is, that it can never be 180° out of phase with the ground ray, which conditions we know are not as a rule fulfilled.

The theory of reciprocity of transmitting and receiving systems has been investigated by Pfrang and Sommerfeld, from whose work and the above reasoning it seems fairly conclusive that the errors with the transmitting Adcock system will be of exactly the same form as with the receiving system.

(12) Practical Considerations.

It has been shown above that with fixed Adcock direction-finding systems there is a possibility of errors as great as 90°, but that the probability of these large errors is fairly small for a receiver or transmitter in which $D/\lambda < 0{\cdot}1$, though for $D/\lambda = 0{\cdot}1$ there are considerable areas in which the error may be 1°, depending on the phase of the downcoming wave. Also in the case of $D/\lambda < 0{\cdot}1$ errors greater than $\frac{1}{4}°$ are accompanied by "fading" such that the resultant electric intensity is only approximately one-quarter of the normal electric intensity in the absence of an atmospheric wave, and decreases approximately inversely as the error increases. On account of this, the probability of error would almost certainly be detected in taking the bearing. If, however, either to obtain enhanced pick-up or in the case of direction-finding with short waves, the spacing is such that $D/\lambda > 0{\cdot}1$, the areas in which errors of several degrees occur is greatly enlarged and the error is not accompanied by such "severe fading," so that it is much less likely that abnormality of the bearing will be suspected. In the above calculations the medium on which the transmitter or receiver is placed has been taken to be a perfect reflector. In general this will not be the case, and this fact will greatly complicate the expressions and may quite likely result in larger errors. Over land the attenuation of the ground wave will be greater, and this will mean that the areas in which errors occur will be nearer the transmitter and also smaller.

In the case of Adcock systems fitted on ships there will always be a likelihood of error, as the effect of the

ship on the wave is to produce a field similar to that due to the presence of both ground and atmospheric waves, and on shorter wavelengths the equivalent down-coming component may be comparable with the direct component, thus giving rise to the possibility of errors and blurred minima, which would not arise with the rotating Adcock system.

ACKNOWLEDGMENTS.

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THE METERING OF E.H.T. SUPPLIES ON THE SECONDARY SIDE OF STEP-DOWN TRANSFORMERS.

By S. H. C. MORTON, Associate Member.

(*Paper* first received 24th September, and in final form 29th December*, 1931; *read before the* METER AND INSTRUMENT SECTION *4th March*, 1932.)

SUMMARY.

The paper deals with a method which could be employed to integrate the input to the primary side of step-down transformers by means of instruments connected in the secondary circuit.

Primary maximum demand, both in kW and in kVA, is considered. In the case of the former a means of measurement is suggested, but to obtain the latter a calculation is necessary. Methods at present in use for the measurement of, and charging for, a supply of this kind are dealt with briefly.

INTRODUCTION.

The rapid expansion in the use of electrical energy, and the closing-down of many of the smaller generating stations, have led to the extension of the areas supplied from one central point. To transmit energy over these greater distances it has become necessary to increase the value of the transmitting pressures. A large consumer may be supplied with power at any pressure up to 132 kV, and the metering of such a supply become a very costly item. If the measurement of this type of supply is carried out on the primary side of a bank of transformers fed by means of a long overhead line, the instrument transformers are in a position of danger when abnormal conditions occur on the line.

These considerations have led to the practice of installing metering equipment on the secondary side of transforming plant, arrangements being made between the supplier and consumer regarding the payment for transformer losses.

METHODS OF CHARGING FOR ELECTRICAL ENERGY.

Two-part tariffs now in general use are based on average maximum demand (taken over a fixed time period) and energy. In the case of the type of supply under consideration the two most common methods of adjusting the account for transformer losses are either to add a fixed portion of the secondary charges to the account or to calibrate the meters to run forward on pressure only to compensate for iron losses, and to register high on load to take copper losses into account. Both these methods are haphazard, as they take no account of the number of transformers on load or excited. In the first case the losses are assumed to vary in direct proportion to the kWh used, and in the second the iron and copper losses are assumed to be a function of the pressure and load respectively.

To illustrate the above point, examples have been worked out and a table (see page 508) has been prepared, showing the cost of a supply metered on the secondary side of transforming plant, and the additional cost of transformer losses and primary maximum demand under various supply conditions. The method of calculation employed is shown in Appendix 1.

Maximum demand in both kW and kVA is considered. The load is supplied through a bank of two transformers, the particulars of which are set out below.

Transformer ratio = 33 000/10 500 volts, delta/star.

Transformer tests:—

Open-circuit:—Volts = 10 500; amps. = 11·5; watts = 15 000.

Short-circuit:—Volts = 2 150; amps. = 52·5; watts = 24 000.

It is assumed that the transformers are used in the following manner:—

(*a*) One transformer only on the 33-kV bars at any time.

(*b*) Two transformers sharing the load.

(*c*) One transformer taking all the load, plus one transformer excited.

The cost of energy per kWh is taken as 0·3d., and the maximum-demand charge as £4 per annum per kVA or kW.

From the Table it can be seen that the difference in cost as registered by meters on the primary and secondary sides of transformers is sufficiently large to make worth while the installation of some additional apparatus in order to integrate the transformer losses and take into account primary maximum demand.

General.

Any supply, the cost of which is based on a two-part tariff and afforded to the consumer through the medium of transforming plant, can be considered to consist of three parts, viz. the secondary kWh, the maximum demand, and the transformer losses. Therefore, when a consumer takes a high-pressure supply and the metering is done on the secondary side of the transforming plant, the supplier should, in order to render accurate accounts, add to the meter registrations a number of units equal to those used in transformer losses during the period for which the account is submitted. In addition the secondary maximum demand should be increased (or decreased, if the maximum demand is based on kVA and the secondary power factor is of such a leading value to warrant it) to a value equal to that taken on the primary side.

The measurement of the kWh used in transformer losses will first be considered. The losses in a transformer can be split into two parts, viz. the iron and the copper losses. The former are a function of the pressure and the latter a function of the current. If the primary and secondary currents and pressures are assumed to bear a definite relationship to each other, and if meters can be obtained which vary with pressure and current

* Originally submitted as a thesis, and accepted as satisfying the examination requirements for Associate Membership.

TABLE OF COSTS.

Showing the Cost per Annum of a Supply of Electrical Energy when the Charges are based on the Registrations of Meters connected in the Secondary Circuit of a Bank of Transformers, and also the Calculated Additional Cost of Transformer Losses.

Transformers in use	Cost per annum, based on the registrations of meters in the secondary circuit	Transformer losses			Cost per annum of transformer losses				Cost of annual transformer losses as a percentage of secondary cost per annum
		Copper loss, kWh per annum	Iron loss, kWh per annum	Difference between primary and secondary maximum demand	Copper loss	Iron loss	Difference between primary and secondary maximum demand	Total	
	£ s. d.				£ s. d.	£ s. d.	£ s. d.	£ s. d.	per cent
One transformer on load. Maximum demand in kW	25 200 0 0	61 500	131 500	32·4 kW	76 17 0	164 7 0	129 12 0	370 16 0	1·47
Two transformers sharing load. Maximum demand in kW	25 200 0 0	30 750	263 000	38·8 kW	38 9 0	328 14 0	155 4 0	522 7 0	2·07
One transformer on load, one excited. Maximum demand in kW	25 200 0 0	61 500	263 000	47·4 kW	76 17 0	328 14 0	189 12 0	595 3 0	2·63
One transformer on load. Maximum demand in kVA. Unity power factor	27 000 0 0	69 600	131 500	49 kVA	87 0 0	164 7 0	196 0 0	447 7 0	1·62
Two transformers on load. Maximum demand in kVA. Unity power factor	27 000 0 0	34 800	263 000	72 kVA	43 10 0	328 14 0	288 0 0	660 4 0	2·45
One transformer on load, one excited. Maximum demand in kVA. Unity power factor	27 000 0 0	69 600	263 000	71 kVA	87 0 0	328 14 0	284 0 0	699 14 0	2·59
One transformer on load. Maximum demand in kVA. Power factor 0·85 lagging	27 000 0 0	69 600	131 500	258 kVA	87 0 0	164 7 0	1 032 0 0	1 283 7 0	4·75
Two transformers on load. Maximum demand in kVA. Power factor 0·85 lagging	27 000 0 0	34 800	263 000	333 kVA	43 10 0	328 14 0	1 332 0 0	1 704 4 0	6·31
One transformer on load, one excited. Maximum demand in kVA. Power factor 0·85 lagging	27 000 0 0	69 600	263 000	385 kVA	87 0 0	328 14 0	1 540 0 0	1 955 14 0	7·25

In all the methods used for supplying the secondary load the number of kWh per annum is assumed to be 12 000 000. The cost per kWh is 0·3d. The total kWh charge is therefore £15 000.

Where the maximum demand is based on kW it is taken as 2 550 kW, the cost of which is £10 200 per annum.

Where the maximum demand is based on kVA it is taken as 3 000 kVA, the cost of which is £12 000 per annum.

in the same way as the losses, it can be seen that their measurement is quite an easy matter. Whilst these assumptions are not quite correct it is shown later that the errors introduced are sufficiently small to be neglected. It is suggested, therefore, that for each transformer (assuming balanced load) two instruments are used for measuring the losses, i.e. the copper-loss meter which is connected in series with the load, and the iron-loss meter which is connected across the supply. In addition to measuring the losses these instruments are capable of indicating the demand in kW required by the losses, and by means of summation gear this demand could be added to the secondary load demand. In these circumstances the indication on the maximum-demand indicator would be approximately equal to the primary maximum demand. Fig. 1 shows the electrical

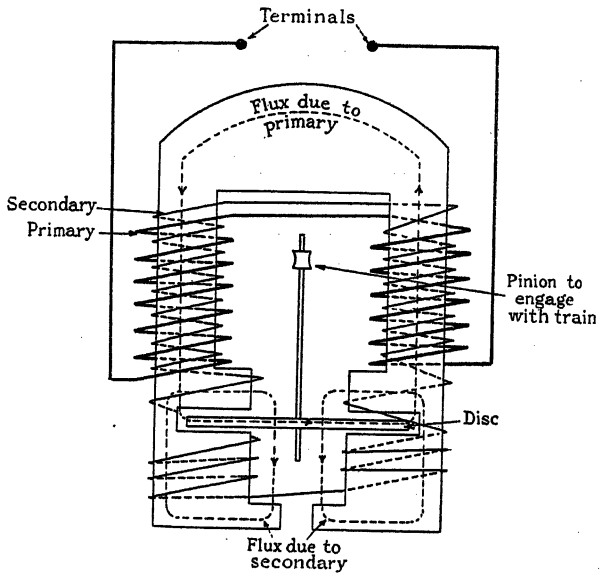


FIG. 1.—Diagram showing the electrical and magnetic circuits of an instrument which could be used (with suitable gearing) to integrate the copper or iron losses of a power transformer.

The terminals shown at the top are connected across the pressure in the case of the iron-loss meter, and in series with the load when instrument is used to integrate the copper losses.

The primary coil (the ends of which are connected to the terminals) and the secondary coil consist of a large number of turns of fine wire when the instrument is used as an iron-loss meter, and of a few turns of thick wire when used as a copper-loss meter.

and magnetic circuits of an instrument which could be used to integrate the iron or copper losses of a power transformer.

An equipment of this type would therefore be capable of measuring the primary input and kW maximum demand.

If the maximum demand is on a kVA basis the problem is much more difficult. No method of direct measurement is available, and it becomes necessary to make a calculation. In order to obtain the particulars required for the calculation the maximum-demand instrument should be of the recording type, and if it does not make a record of both kW and kVA a recording power-factor meter is necessary. A recording voltmeter should also be installed. From these instrument charts and the open-circuit and short-circuit tests of the power transformers, sufficient information should be available to calculate the primary pressure and current. If more than one transformer is on load no difficulty is presented, but in the case of transformers excited at the time of maximum load it is impossible to calculate the primary kVA unless an instrument to record the primary switching operations is installed. The fact that iron-loss units are being registered would, in all probability, prevent a consumer from exciting a transformer unnecessarily and would thereby allow the calculation to be made with reasonable accuracy.

Transformer Tests.

To obtain the data necessary for the calibration of the copper-loss and iron-loss meters a series of short-circuit and open-circuit tests should be taken on the power transformers. The open-circuit tests should be carried out at as frequent intervals as possible, from about 15 per cent under-pressure to 10 per cent over-pressure, and the short-circuit tests should extend from 25 per cent to 110 per cent of full load. If the losses (in watts) are then plotted against pressure and current respectively, the laws of the curves to which the instruments are to be calibrated can be obtained.

Iron-Loss Meters.

The iron losses of a transformer can be split into two parts, those due to hysteresis and those due to eddy currents. To arrive at the variations of the losses with varying frequency and constant pressure, using the Steinmetz formula we have:—

$$\text{Hysteresis losses} = kfB^{1\cdot6} \times 10^{-7}$$

$$B = \frac{0\cdot4\pi IN\mu}{l}$$

where I = current,
N = number of turns,
μ = permeability,
l = length of iron, cm.

Assuming the resistance to be small compared with the impedance, we have

$$I = \frac{E}{2\pi fL}$$

and, as E is constant, $B = K\frac{1}{f}$

Hysteresis losses therefore vary as $\frac{1}{f^{0\cdot6}}$.

Eddy-current losses $= kf^2B^2$, and as B is proportional to $1/f$ they must be unaffected by frequency.

The losses would, therefore, follow a law of the form

$$y = a + bx^n$$

If it is assumed that the eddy-current and hysteresis losses are 0·2 and 0·8 respectively of the total iron losses, the formula would become

$$\text{Losses} = K\frac{1}{f^{0\cdot483}}$$

When the pressure varies and the frequency is constant, it can be seen from the foregoing equation that the hysteresis losses would vary as $E^{1\cdot6}$, and the eddy-current losses as E^2. Again, taking the hysteresis losses to be 80 per cent and the eddy-current losses 20 per cent of the iron losses, the formula for variation of iron losses with pressure would be:—

$$\text{Losses} = KE^{1\cdot68}$$

In modern stations it is becoming the common practice to install some means of frequency control, and it is therefore unnecessary to take any account of the variation of iron losses due to frequency fluctuation.

The Steinmetz formula for iron losses is a purely empirical one, and, since it was arrived at, the iron used for transformer cores has altered considerably. The approximate variations of these lossses with respect to voltage in the case of stalloy are given below.

B, lines per cm²	Losses proportional to
11 000	E^2
12 500	$E^{2\cdot3}$
13 500	E^3
14 500	E^4

For a good transformer operating on a 50-cycle circuit the flux density would be in the region of 13 000 to 13 500 lines per cm². Assuming the latter density, the iron losses can be said to vary as E^3.

In order, therefore, to measure the iron losses of a transformer correctly it is necessary to have a meter the registrations of which would vary as E^3. There is, of course, no meter which satisfies this condition, but it is suggested that the errors introduced by using an ordinary induction instrument are small enough to be neglected. The instrument proposed would consist of a magnetic circuit containing two coils, one of which would be connected across two phases of the supply in conjunction with a potential transformer, the other forming a closed circuit.

The coil connected across the supply would have flowing in it a current proportional to the pressure. The flux produced by this current would cross an air-gap in which would be suspended, free to rotate, an aluminium disc. Current would be induced in the closed coil, which would act like the secondary of a transformer. This would be arranged so that the flux produced by the current flowing in it would cross the gap in a direction at right angles to the main flux. These two fluxes would be in correct time and space relation to produce a torque which would be proportional to E^2.

When the instrument is produced, the dial will have to be calibrated to register kWh. To do this an open-circuit test of the transformer, the losses of which are to be measured, is necessary. The dial of the instrument would therefore integrate losses (KE^2 hours), K being calculated from the pressure point on the open-circuit curve at which the transformer would normally be working.

In order to investigate the errors which would be introduced by using an instrument of this kind, let us assume that it has been calibrated so that it correctly integrates the iron losses on a transformer when the transformer is excited with normal pressure and the secondary is carrying no load.

The transformer ratio is 33 000/11 000 volts (delta/star).

The short-circuit test-figures taken on the primary side are:—

Volts = 2 150, amperes = 52·5, watts = 23 100;

and the open-circuit test taken on the secondary side gives the following:—

Volts = 11 000, amperes = 11·6, watts = 14 400.

Transferred to primary:—Iron losses = 14·4 kW at 33 000 volts.

The iron losses vary as E^3, where E is the primary pressure. The meter gearing would be so arranged that the meter would read in units and obey the following law:—

Units = $0\cdot119 \times 10^{-6}\ V^2$ hours (V being the secondary phase-to-phase pressure).

On open-circuit with 33 kV impressed on the primary winding and a terminal pressure of 11 kV on the secondary, the iron losses would be 14·4 kW and the meter would therefore register correctly.

At 31 500 volts on the primary

$$\text{Losses (varying as } E^3) = \frac{14\cdot4 \times 31\,500^3}{33\,000^3} = 12\cdot5\,\text{kW}$$

The meter would indicate $0\cdot119 \times 10\,500^2 \times 10^{-6}$
$= 13\cdot12$ kW

This is 5·0 per cent high.

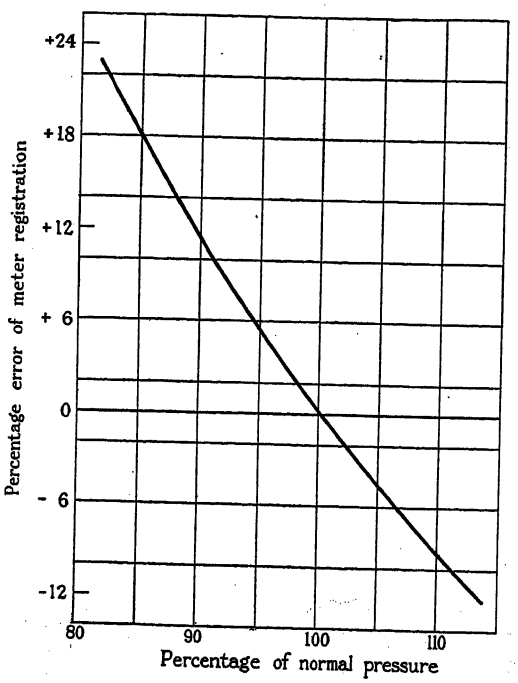


FIG. 2.—Curve showing errors of iron-loss meter with varying primary pressure on power transformer. Transformer on open circuit.

The errors from 27 000 volts to 37 500 volts are shown in Fig. 2.

To find the errors of the meter at different loads and power factors the pressure at which it will operate can be arrived at by means of Fig. 3. (This assumes all resistance and reactance to be on the secondary side.)

From this diagram it can be seen that

$$E^2 = V^2 + e_z^2 - 2Ve_z[-\cos(\psi - \phi)]$$
$$= V^2 + e_z^2 + 2Ve_z(\cos\psi\cos\phi + \sin\psi\sin\phi)$$

where e_z = voltage due to impedance,
e_x = voltage due to reactance,
e_r = voltage due to resistance,
V = secondary pressure (phase to neutral),
E = primary pressure in terms of secondary phase-to-neutral voltage.

As $\cos\psi = e_r/e_z$ and $\sin\psi = e_x/e_z$,

$$E^2 = V^2 + e_z^2 + 2V(e_r\cos\phi + e_x\sin\phi)$$

From the short-circuit test we have, at full load per primary coil,

$V_1 = 2\,150$; $I = 30{\cdot}6$ amperes; watts $= 7\,700$.

Transferring to secondary,

$$\text{Coil ratio of transformation} = \left(\frac{33\,000 \times \sqrt{3}}{11\,000}\right) = 5{\cdot}2$$

$V_1 = 414 = e_z$; $I = 157{\cdot}5$ amperes; watts $= 7\,700$;

$$e_r = \frac{7\,700}{157{\cdot}5} = 49 \text{ volts};$$

$e_x = \sqrt{[414^2 - 49^2]} = 411$ volts.

The secondary pressure at full load, unity power factor, when the primary pressure is 33 kV, is 6·350

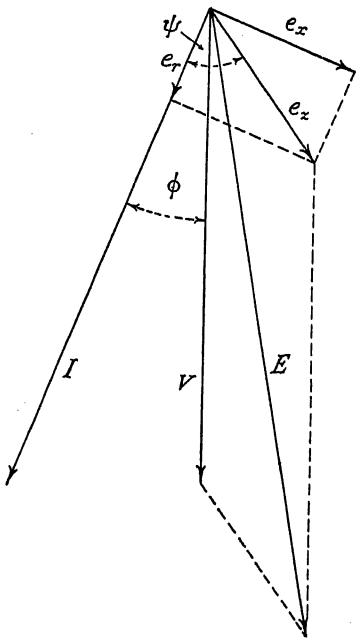


FIG. 3.

volts, assuming that there is no drop due to impedance. Therefore

$$6\,350^2 = V^2 + 414^2 + 2V(49 \times 1 + 411 \times 0)$$

whence $V = 6\,287$.

$$\text{Meter registration} = 0{\cdot}119 \times 10^{-6} \times (6\,287 \times \sqrt{3})^2 = 14{\cdot}11 \text{ kW}$$

Error in registration $= 2{\cdot}0$ per cent low.

Fig. 4 has been drawn to show the errors which are introduced into the meter when the power factor is varied and the transformer working on full load.

Under normal circumstances, as the load increases and the angle between the current and pressure becomes greater (assuming the current to be lagging), the terminal pressure on the transformer primary decreases. The amount by which the pressure falls depends upon the length of the line and the line-constants. On examining the two curves it can be seen that a fall of primary pressure will cause the iron-loss meter to register high, whilst an increase of load and a decrease of lagging power factor will have the opposite effect. A similar balancing of errors will occur if the power factor is leading.

In the case of the transformer operating at 0·85 lagging power factor on full load, causing a fall in supply pressure of 5 per cent, a positive error of about 5 per cent would be introduced in the meter by the fall of supply pressure, whilst a negative error of 8·3 per cent would be caused by transformer regulation. This would mean an error in registration of about 3·3 per cent in the meter, which at full load would be only 3·3 per cent of 0·5 per cent (approx.) of the power supplied. This is an error very much smaller than that to which the main meters can be calibrated.

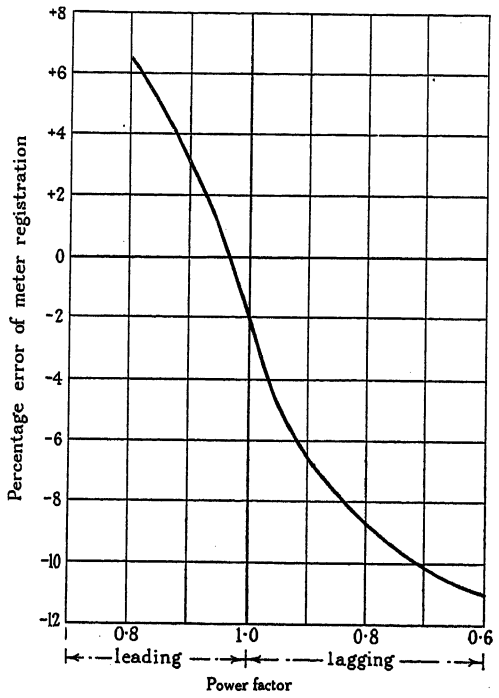


FIG. 4.—Curve showing errors in iron-loss meters. Power transformer on full load with varying power factor. Primary pressure normal.

Copper-Loss Meters.

The copper losses of a transformer vary almost as the square of the current, and for all practical purposes this relationship can be considered to be correct, neglecting, for the moment, variations due to temperature.

A meter to measure these losses presents a rather different problem from that for the iron losses, as in the latter the pressure only varies within fairly small limits but the current can have any value from zero to 125 per cent of full load. The effective range of an induction instrument is from full to 1/25th load. A meter measuring copper losses which vary as I^2 could be considered accurate from full to 1/5th load of the transformer, the copper losses at the lower point being only 4 per cent of those at full load. Careful design and good workmanship could extend this range, and it might be possible to obtain accurate registration from 125 per cent to 1 per cent of full load on the meter. The copper losses of a transformer vary with temperature. This variation can be assumed to be equal to 0·00428 per degree C.

A temperature-rise of 50 deg. C. in a transformer would therefore cause an increase in copper losses of 21·4 per cent. Assuming a transformer to be working on a constant load and the difference between maximum and minimum air temperature to be 40 deg. C. the copper losses would vary by 17·12 per cent. The copper-loss meter would be installed in a building of some sort and in most cases the temperature variation would not be very great. The meter itself would, of course, be affected by temperature, but this variation would be small and for all practical purposes could be neglected. The registrations of the instrument can therefore be said to depend entirely on current, whilst the losses to be measured will also vary with the temperature of the transformer windings, which in turn are affected by the air temperature and the load.

To arrive at a constant for the calibration of the instrument it is necessary to decide on some average value of air temperature and temperature-rise of the transformer. The former can be obtained by studying the temperature records for the district in which the transformer is to be installed. The average temperature can then be used in obtaining the constant. In practice it is doubtful whether the trouble entailed is worth while, as a pure assumption has to be made of the transformer temperature and an error of 10 deg. C. in an estimate would only cause an error of approximately 4 per cent in the meter, and at full load this would be only about 0·04 per cent of the total load taken.

Assume that the air temperature in the district in which the transformer is installed varies from a minimum of − 8° C. to a maximum of 36° C. (the average being + 14° C.) and that the maximum rise in temperature of the transformer is 40° C. For the purpose of calibrating the copper-loss meter the temperature of the transformer can be taken as

$$\frac{36 - 8}{2} + \frac{40}{2} = 34° \text{ C.}$$

and the meter can be arranged to register correctly when this condition is fulfilled.

In order to arrive at the errors introduced by this assumption, take a transformer the losses of which are $(\text{kW})_0$ when the temperature of the transformer windings is 34° C. The maximum losses would occur when the air temperature is 36° C. and the transformer temperature-rise 40 deg. C., making a total of 76° C.

$$\text{Losses at } 76° \text{ C.} = (\text{kW})_0\{1 + 0{\cdot}00428\,(76 - 34)\} = 1{\cdot}1795\,(\text{kW})_0$$

The meter would register $(\text{kW})_0$, and the error taken as a percentage of the actual losses would be 15·2 per cent low. The minimum losses would occur when the transformer is switched on full load, the temperature of the windings being − 8° C.

$$\text{Losses at } -8° \text{ C.} = (\text{kW})_0\{1 - 0{\cdot}00428\,(34 + 8)\} = 0{\cdot}8205\,(\text{kW})_0$$

The error in meter registration (taken as in the previous case) will be 21·9 per cent high.

If the transformer copper losses at full load are 1 per cent of full load, the maximum error introduced into the total supply will be only 21·9 per cent of 1 per cent, or 0·22 per cent.

Maximum Demand in kW.

In order to measure correctly a supply on the usual 2-part tariff the maximum demand of which is based on kW, provision must be made to add to the main secondary load the loads due to transformer losses. To do this, summation gear could be employed. This should be of the contactor type, in which impulses are transmitted from the meters to a separate summation meter. Dials are provided on the latter for each individual meter for checking purposes. The impulses which record the different meter readings are transmitted to these dials and also to a common spindle which operates the summation dial and the maximum-demand pointer.

Provision should be made on the summation meter for two dials per transformer to be operated by the copper-loss and iron-loss meters respectively, in addition to that for the secondary load. The use of this type of apparatus will enable the primary units and maximum demand to be arrived at with a fairly high degree of accuracy.

Maximum Demand in kVA.

As previously pointed out, many sources of inaccuracy manifest themselves when a calculation to obtain primary kVA has to be made. Against this, however, there is the fact that the result of such a calculation would be more accurate than any other means which could be adopted, with the exception of actual measurement on the high-pressure side of the transformer. By using the instruments suggested earlier, we can determine the secondary maximum demand in kVA and/or in kW, and the secondary power factor and secondary pressure. We also have the transformer short-circuit and open-circuit tests. With these data we are able to make the calculation in the following manner:—

Two sets of curves should be drawn. The first set should show the variations of both impedance voltage and copper losses (in watts) with varying load currents. The short-circuit tests, from which these results are obtained, will usually be taken on the primary side, and it will be found an advantage to plot the curves with equivalent secondary values.

The second set of curves, obtained from the open-circuit tests, should show the variation of no-load current and iron losses (in watts) with varying line pressure.

To obtain the primary pressure in terms of the secondary, the first-mentioned curves are used. The impedance voltage and the watts loss due to resistance, corresponding to the main secondary current, are found. The primary pressure (in terms of the secondary) can then be calculated by means of the formula

$$E^2 = V^2 + e_z^2 + 2V(e_r \cos\phi \pm e_x \sin\phi)$$

where V = secondary pressure,
e_z = impedance voltage,
e_r = voltage due to resistance,
e_x = voltage due to reactance,
ϕ = angle of lag between pressure and current.

The sign between the terms in brackets is positive for a lagging power factor and negative when the power factor is leading. The value of the current is found in a similar manner.

From Fig. 5 it can be seen that

$$I_p^2 = I_s^2 + I_0^2 + 2I_s(I_e \cos\phi \pm I_m \sin\phi)$$

By using the second set of curves the no-load current I_0 at the pressure E can be found. The iron loss in watts

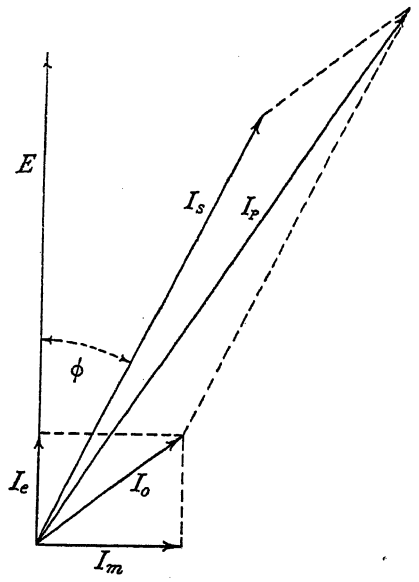


FIG. 5.

can also be obtained and from this I_e calculated, I_m being the base of the right-angled triangle of which I_0 is the hypotenuse. The kVA can be calculated from the pressure and current in the usual way.

In Appendix 2 an example has been worked out, using figures taken from a supply which is measured by means of an equipment on the basis of that outlined herein.

Position of Instruments in the Circuit.

One iron-loss meter operated by means of a single-phase potential transformer is required to measure the iron losses of each power transformer installed. This potential transformer should be connected in such a position that it is energized when the high-pressure switch is closed.

The number of copper-loss meters required varies according to the nature of the load. In the case of a balanced load one only is necessary, but if the load is unbalanced three instruments should be used. These instruments will be operated by means of current transformers connected in the transformer secondary circuit and will not function unless the transformer is on load. The instruments for measuring the secondary load would be connected in the usual manner between the incoming and outgoing feeders. Fig. 6 indicates these connections.

Cost of Equipments.

The tables in Appendix 3 have been prepared in order to compare the cost of metering equipments of the type outlined in this paper with equipments connected in the primary circuit of power transformers. In the latter equipments the apparatus consists of two kWh meters, one maximum-demand indicator, one maximum-demand recorder, two sets of current transformers, and two single-phase potential transformers. In the former the main metering is the same, except that the two single-phase potential transformers have been replaced by one 3-phase transformer. Additional

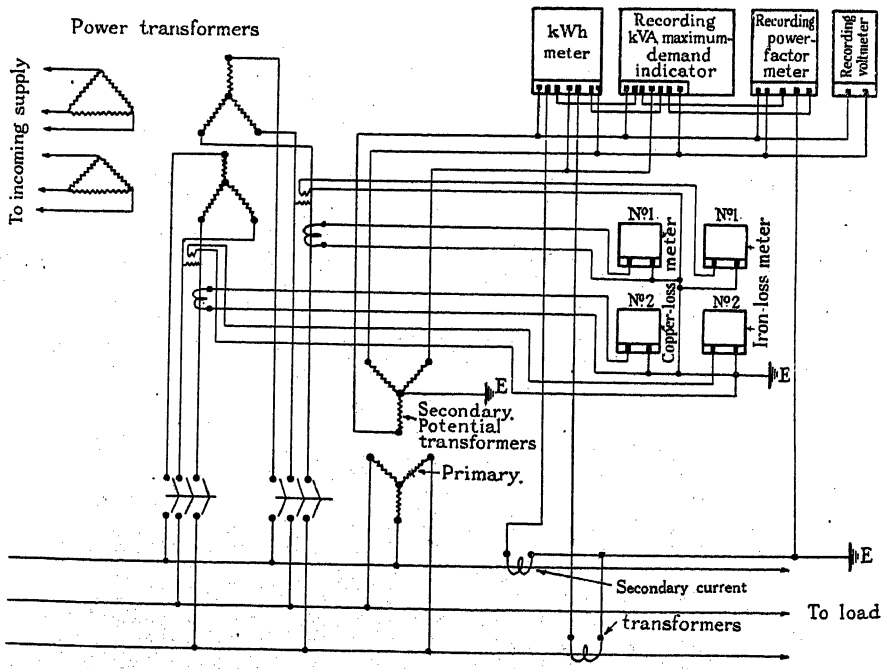


FIG. 6.—Diagram of connections of a metering equipment measuring a supply of electrical energy on the secondary side of a bank of two transformers, and integrating the copper and iron losses. The maximum demand is on a kVA basis.

apparatus is also included for measuring transformer iron and copper losses. The cost of testing and installing is not included.

The supply to be metered is assumed to consist of three 3 000-kW transformers, ratio 33 000/11 000 volts, supplying a balanced load.

Although the cost of the equipment is a matter of importance the safety of the apparatus should also be very carefully considered before a final decision is made regarding the type of metering to be installed.

Conclusion.

The author has suggested in the paper a means of improving the present method of metering e.h.t. supplies on the secondary side of step-down transformers, but he has not advanced it as an argument in favour of installing meters in that position. On the contrary, if financial and technical considerations allow, the metering should always be done on the incoming supply side.

The installation of recording instruments when the maximum demand is charged on a kVA basis may perhaps appear at first sight to be a complication peculiar to the arrangements suggested in the paper. In actual practice, however, the author has found it well worth while to use maximum-demand instruments of this type for the larger consumers, as useful information can be obtained from the charts and complaints can be readily adjusted.

Acknowledgments.

The author would like to express his indebtedness to the West Gloucestershire Power Co., Ltd., and to Mr. H. S. Ellis, the general manager and chief engineer of that company, for their kindness in providing facilities for obtaining the data contained in the paper. He also wishes to thank Mr. E. W. Hill of the Aron Electricity Meter, Ltd., Mr. G. L. Porter of Ferranti, Ltd., and the Metropolitan-Vickers Electrical Co., Ltd., who have supplied much useful information.

APPENDIX 1.

Calculation to Obtain Figures for Table of Costs.

Transformer Particulars.

Ratio = 33 000/10 500 volts, delta/star, size 3 000 kVA.
Open-circuit tests (taken on secondary side):—

Volts = 10 500, current = 11·5 amperes, watts = 15 000.

Short-circuit tests (taken on primary side):—

Volts = 2 150, current = 52·5 amperes, watts = 24 000.

Maximum Demand in kW.

One transformer only on 33-kV busbars.
Maximum demand on secondary = 2 550 kW.
Units per annum .. .. .. = 12 000 000.
Iron-loss units per annum = 15 × 8 760 = 131 500.
Maximum demand due to iron losses .. .. = 15 kW.
Maximum demand due to copper losses at 44·7 primary amperes .. .. = 17·4 kW.

Copper-loss units (load factor 53·9 per cent):—
Assumed form factor on above load factor .. .. .. = 1·18.
R.M.S. value of primary current
$$= \frac{44{\cdot}7 \times 53{\cdot}9}{100} \times 1{\cdot}18 \quad .. = 28{\cdot}4 \text{ amperes.}$$
Average value of copper losses .. = 7·02 kW.
Copper-loss units per annum
8 760 × 7·02 = 61 500.

The figures for the other two cases when the maximum demand is in kW are arrived at in a similar manner.

Maximum Demand in kVA (Power Factor 1·0).

One transformer only on 33-kV busbars.
Maximum demand on secondary = 3 000 kVA.
Ratio of transformation per coil = 5·44.

Transferring short-circuit test to secondary side we have per coil:—

Volts = 396, current = 165 amperes, watts = 8 000.

From this we obtain:—

$$e_z = 396, \quad e_r = 48{\cdot}5, \quad e_x = 393,$$

where e_z = voltage-drop due to impedance,
e_r = voltage-drop due to resistance,
e_x = voltage-drop due to reactance.

Secondary voltage is assumed to be 10 500 volts, therefore $V = 6\,060$.

$$E_p^2 = V^2 + e_z^2 + 2V(e_r \cos\phi + e_x \sin\phi)$$
$$= 6\,060^2 + 396^2 + 2 \times 6\,060(48{\cdot}5 \times 1)$$

whence $E_p = 6\,122$ volts.

$$I_p^2 = I_s^2 + I_0^2 + 2I_s(I_e \cos\phi + I_m \sin\phi)$$

where I_p = primary current in terms of secondary,
I_s = secondary current = 165 amperes,
I_0 = no-load current = 11·5 amperes,
I_e = no-load energy current = 0·83 amperes,
I_m = magnetizing current = 11·5 amperes (approx.).

$$\therefore I_p^2 = 165^2 + 11{\cdot}5^2 + 2 \times 165(0{\cdot}83 \times 1)$$
$$\therefore I_p = 166 \text{ amperes.}$$
$$\text{kVA} = \frac{166 \times 6\,122 \times 3}{1\,000} = 3\,049$$

Units used in iron losses per annum = 131 550 (average pressure assumed to be 10 500 volts).
Copper losses (load factor 45·6 per cent):—
Form factor at above load factor assumed to be 1·26.
Maximum current on primary = 52·5 amperes.
$$\text{R.M.S. current} = \frac{52{\cdot}5 \times 45{\cdot}6}{100} \times 1{\cdot}26$$
$$= 30{\cdot}2 \text{ amperes.}$$
Average value of copper losses = 7·94 kW.

Units used in copper losses per annum = 7·94 × 8 760 = 69 600.

The same method is employed for obtaining all the other figures when the maximum demand is based on kVA.

APPENDIX 2.

CALCULATION OF KVA.

Transformer Tests.

Ratio = 33 000/10 500 volts, delta/star.
Transformer rating = 3 000 kVA.

Open-circuit tests (taken on secondary side):—

Volts	Amperes	Watts
9 490	3·55	9 210
10 280	6·28	11 550
11 000	11·58	14 400

Short-circuit tests (taken on primary side):—

Volts	Amperes	Watts
1 985	47·7	17 000
2 470	59·5	26 400
1 496	36·1	9 600

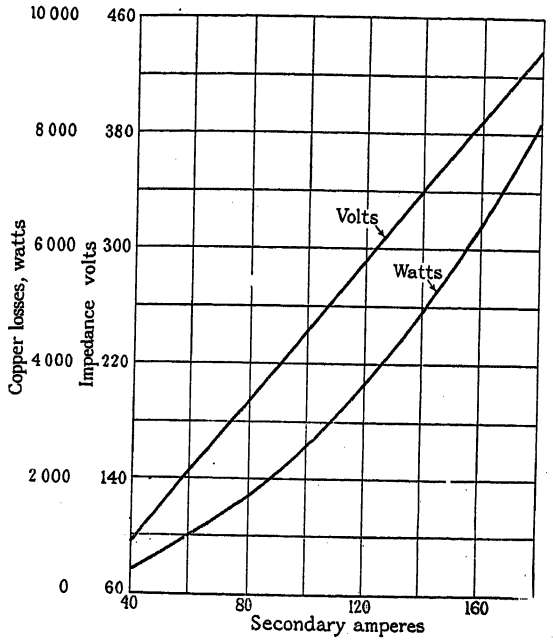


FIG. 7.—Short-circuit tests (transferred to secondary side). Curves (coil figures) showing variation of copper losses (in watts) and impedance volts with varying secondary currents.

Calculation of Equivalent Primary Pressure.

Primary is connected in delta, therefore the short-circuit tests per coil are as follow:—

Volts	Amperes	Watts
1 496	20·8	3 200
1 985	27·5	5 667
2 470	34·4	8 800

Secondary coil pressure = 10 500/$\sqrt{3}$.
Coil ratio = (33 000/10 500)$\sqrt{3}$ = 5·44.
Short-circuit tests per coil (transferred to secondary):—

Volts	Amperes	Watts
275	115	3 200
365	149·5	5 667
455	187	8 800

From these figures Fig. 7 is produced.
Fig. 8 is drawn from the actual test-figures.

From these curves and the instrument charts the primary kVA can be found.

Assume that at the time of maximum demand the charts give the following results:—

Maximum demand on secondary = 2 800 kVA.
Simultaneous power factor .. = 0·92 (lagging).
Simultaneous secondary pressure = 10 200 volts.

To Find Pressure.

Secondary load current .. .. = 158·5 amperes.
Secondary pressure V per coil .. = 5 900 volts.

From the short-circuit curves:—

Impedance pressure e_z per coil at 158·5 amperes = 386 volts.
Watts per coil at 158·5 amperes = 6 350.
Drop e_r due to resistance

$$= \frac{6\,350}{158\cdot5} = 40 \text{ volts (approx.)}.$$

Drop e_x due to reactance

$$= \sqrt{[386^2 - 40^2]} = 384 \text{ volts}.$$

Where E is the equivalent primary pressure we have (see page 512)

$$E^2 = V^2 + e_z^2 + 2V(e_r \cos\phi + e_x \sin\phi)$$
$$= 5\,900^2 + 386^2 + 2 \times 5\,900 \times (40 \times 0\cdot92 + 384 \times 0\cdot39)$$

whence E = 6 094 volts.
Line pressure = 10 550 volts.

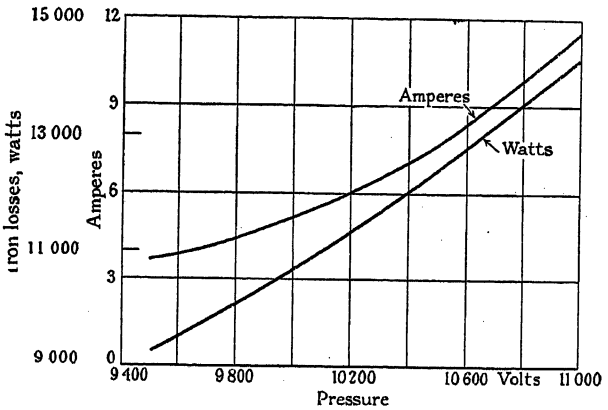


FIG. 8.—Open-circuit tests taken on secondary side of transformer. Curve showing the variation of iron losses (in watts) and current with varying pressure on transformer.

To Find Current.

No-load current I_0 at 10 550 volts = 8·0 amperes.
Watts (total) at 10 550 volts .. = 12 450.
Energy component I_e of no-load current .. .. = 0·68 ampere.
Magnetizing current I_m .. .. = 7·9 amperes (approx.).

From page 513 we have:—

$$I_p^2 = I_s^2 + I_0^2 + 2I_s(I_e \cos\phi + I_m \sin\phi)$$
$$= 158\cdot5^2 + 8^2 + 2 \times 158\cdot5 \times (0\cdot68 \times 0\cdot92 + 7\cdot9 \times 0\cdot39)$$

whence I_p = 162·4 amperes.

$$\text{Calculated primary kVA} = \frac{10\,550 \times 162\cdot4 \times \sqrt{3}}{1\,000}$$
$$= 2\,966 \text{ kVA}.$$

APPENDIX 3.

Relative Costs of Metering Equipments.

Maximum demand	No.	Metering equipment on the primary side of transforming plant	Price each	Total	No.	Metering equipment on the secondary side of transforming plant with copper- and iron-loss metering	Price each	Total
			£ s. d.	£ s. d.			£ s. d.	£ s. d.
On a kW basis	2	Outdoor-type potential transformers, 33 000/110 volts ..	96 10 0	193 0 0	1	Three-phase potential transformer, 11 000/110 volts, complete with fuses	38 4 3	38 4 3
	2	Sets of fuses for potential transformers	8 10 0	17 0 0	3	Single-phase potential transformers, 11 000/110 volts ..	24 0 0	72 0 0
	4	150/5-ampere current transformers, Class A accuracy, 15-VA capacity	52 8 6	209 14 0	4	500/5-ampere current transformers, Class A accuracy, 15-VA capacity	16 0 0	64 0 0
	1	Three-phase, 3-wire meter with maximum-demand indicator, 150/5 amperes, 33 000/110 volts	16 12 0	16 12 0	3	150/5-ampere current transformers, Class C accuracy, 5-VA capacity	4 16 0	14 8 0
	1	Three-phase, 3-wire meter as above but with contact device to operate demand-recording mechanism ..	10 15 0	10 15 0	1	Three-phase 3-wire meter with maximum-demand indicator, 500/5-ampere, 11 000/110 volts	16 12 0	16 12 0
	1	Maximum-demand recording mechanism	69 0 0	69 0 0	1	Meter as above but with contact device to operate summator .	10 15 0	10 15 0
					1	10-way summator with printometer and maximum-demand indicator	238 10 0	238 10 0
					3	Copper-loss meters with contact device to operate summator .	10 0 0	30 0 0
					3	Iron-loss meters with contact device to operate summator .	10 0 0	30 0 0
		Total	—	£516 1 0		Total	—	£514 9 3
On a kVA basis	2	Outdoor-type potential transformers, 33 000/110 volts ..	96 10 0	193 0 0	1	Three-phase potential transformer, 11 000/110 volts, complete with fuses	38 4 3	38 4 3
	2	Sets of fuses for potential transformers	8 10 0	17 0 0	3	Single-phase potential transformers, 11 000/110 volts ..	24 0 0	72 0 0
	4	150/5-ampere current transformers, Class A accuracy, 15-VA capacity	52 8 6	209 14 0	4	500/5-ampere current transformers, Class A accuracy, 15-VA capacity	16 0 0	64 0 0

On a kVA basis—*contd.*	1	Meter consisting of sine and cosine portions with kWh dial and kVA maximum-demand pointer	33 11 0	33 11 0
	1	Meter as above but with contact device to operate demand-recording mechanism	36 19 0	36 19 0
	1	Maximum-demand recording mechanism	69 0 0	69 0 0
		Total	—	£559 4 0

3	150/5-ampere current transformers, Class C accuracy, 5-VA capacity	4 16 0	14 8 0
3	Copper-loss meters	1 15 0	5 5 0
3	Iron-loss meters	1 15 0	5 5 0
1	Recording voltmeter	20 0 0	20 0 0
	Total	—	£219 2 3
	Alternative No. 1 for obtaining kVA maximum demand, units and power factor.		
1	Meter with sine and cosine portions, kWh dial and kVA maximum-demand pointer	33 11 0	33 11 0
1	Meter with sine and cosine portions, kWh dial, and kW and kVA maximum-demand record	80 0 0	80 0 0
	Brought down from above	—	219 2 3
	Total	—	£332 13 3
	Alternative No. 2 for obtaining kVA maximum demand, units and power factor.		
1	Meter with sine and cosine portions, kWh dial, and kVA maximum-demand pointer	33 11 0	33 11 0
1	Meter with sine and cosine portions, kWh dial but fitted with contact device for operating recording maximum-demand indicator	36 19 0	36 19 0
1	Recording maximum-demand instrument operated by the above meter	69 0 0	69 0 0
1	Recording power-factor meter	70 0 0	70 0 0
	Brought down from above	—	219 2 3
	Total	—	£428 12 3

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 4TH MARCH, 1932.

Mr. E. Fawssett : While I disagree to some extent with the general methods advocated in the paper, financial and technical considerations never allow the metering to be done on the incoming supply side if there is any suitable alternative, assuming (and this is a big assumption) that it is necessary to measure the transformer losses accurately. The phase-angle characteristic of a current transformer of modern design, with plenty of ampere-turns and a mumetal core, consists in essence of two straight lines nearly at right angles, corresponding to no change or very great change of phase-angle with load. When one is trying to measure the iron losses on a power transformer, which may have a power factor of 0·15, the current transformer is working on the latter characteristic, the error in the meter reading being 20 to 30 per cent due to the current transformer. The particular problem dealt with by the author is not very representative of those the average power company has to deal with in everyday practice. The more general case with which we have to deal on the North-East Coast is the transformation of 33, 20, or 11 kV, to 3 kV for collieries and 440 volts for the average manufacturer. The author is a little unkind to other possible methods of adjusting the account for transformer losses when he describes these as " haphazard." Further, he is incorrect in stating that in the second method mentioned " the iron and copper losses are assumed to vary as the pressure and load respectively." The creep characteristic of an induction watt-hour meter is such that the speed varies as the square of the applied pressure, and it closely approximates to the usual iron-loss curve. On page 510 the author gives some interesting figures which eventually lead to the conclusion that for a 50-cycle transformer working at normal voltage, changes in voltage cause the iron losses to vary as E^3. The following figures are the mean values obtained from 6 different modern 3 000-kVA transformers with 50-cycle 20 000-volt primaries and 2 875-volt secondaries:—

kV	Percentage of normal	E^2	kW loss	Relative loss
		per cent		
18	90	81	5·3	80·3
20	100	100	6·6	100
22	110	121	7·9	119·7

According to these values the iron losses are roughly proportional to E^2, and the power factor of the magnetizing current is considerably lower than that associated with older transformers. The power factor that the metering current transformer has to deal with is about 0·1 at about 1 per cent of full load, and if this value is representative of modern practice Fig. 2 rather overstates the error of the iron-loss meter. On page 512 the author arrives at a mean temperature of 34° C. the purpose of calibrating the copper-loss meter. iew of the fact that most of the registration of opper-loss meter will be at high load, that temperature ought to be a weighted average, and not the arithmetic mean of the two outside temperatures: instead of 40 ÷ 2, a figure nearer 27 or 28 should be inserted, giving a calibrating temperature of 42° C. With regard to Fig. 5, if the kW demand only is required this equipment is too complicated and too expensive, in view of the fact that it has to deal with only about 2 or 3 per cent of the whole bill. Possibly, however, it might be justified if the copper-loss and iron-loss meters were really correct over a wide range and the annual bill were extremely heavy. I should like to register a plea for " compensated " metering, which seems to me to be both cheap and accurate. We have employed it for some years and it has never involved us in a dispute with a consumer. I will take as an illustration a fairly small supply through a single transformer, assuming open-type high-tension metering and 100-ampere-primary current transformers. The cost of good-quality equipment incorporating one polyphase h.t. meter would be £68. Low-tension compensated equipment, on the other hand, would mean an ordinary 440-volt meter with 2 000/5 current transformers, which would have a vastly better performance. This would cost about £15 plus a special calibration charge (about £10) for bringing in the iron and copper losses, or a total of £25, as against £68 for h.t. metering. We might apply similar reasoning to the author's Appendix 3. I would solve his problem by installing a single polyphase meter in each of the secondary sides of the two main transformers, so that each one would be energized when its own particular transformer was alive. I would get the demand by summing the currents from those two individual circuits on a third master meter, and make that the demand meter, the voltage for it being provided through a selector relay. This scheme, with the exception of the iron-loss compensation device, is being adopted by the Central Electricity Board on minor supplies. The cost of such an equipment would be about £170, as compared with £516 for straight metering. The iron-loss registration, which is obtained by setting a straight creep on the meter from previous level compensation, is almost exactly proportional to E^2 over the range of voltage likely to be encountered. The current creep is obtained most satisfactorily by electrical unbalancing. If a meter has 10 turns on either current coil, unbalancing to the extent of 1 turn will give just about the right amount of current creep for the average power-transformer copper loss if the power transformer and the main metering equipment are of the same output. At one time it was impossible to combine shunt and series running so as to fit the theoretical curve throughout the range; the meter was too fast at about half load and too slow at full load. With the modern meter, however, which has a much better curve than the type in use 5 years ago, it is possible by combining shunt and series creep to fit the theoretical curve exactly. The technical justification for this scheme is, in brief: (*a*) Creep correct and reasonably constant; (*b*) far better current transformers, with a much safer design; (*c*) copper loss can be corrected for with reasonable accuracy;

(*d*) far more accurate readings obtainable than direct e.h.t. metering can be expected to give.

Mr. H. S. Dransfield: A serious objection to the arrangement suggested in the paper is that, if there were a dispute with the consumer, it would be difficult for him to understand exactly how the arrangement worked. The author describes a complicated arrangement for measuring the maximum demand on the primary side; it seems to me that if he measured the straight maximum demand on the secondary side, the maximum demand on the primary side could be arrived at quite efficiently by adding on paper a suitable amount. For many reasons, I should be inclined to separate the two parts of these charges as far as possible. If the iron losses in the transformer appeared large, as at a time of light load, there would be a considerable reading on the meter even when the consumer was possibly using no current at all, and this could lead to misunderstanding. I once met with an instance where the transformer had to remain switched in for a long week-end to supply the caretaker with current for two lamps. The cost of lighting apparently worked out at about 1s. per unit, and it was difficult to persuade the consumer that he was not being overcharged. I should like more details of the characteristics of the special instrument which is being used in the author's scheme. Does it conform to the usual British Standard Specification with regard to accuracy? The author states that under some conditions he would require records of the high-tension switching operations; but as such switching is usually beyond the control of the meter department, I doubt whether in practice it would always be possible to get reliable records. The losses on the transformers are in many cases so small in proportion to the total load that it is doubtful whether the errors of the meters—no matter on what side of the transformers these were put—would not be greater than the losses expressed as a percentage of the total units. In certain cases I computed the loss with the aid of an hour meter and time switch, making allowance for load factor. This method has worked quite well and no difficulty has been experienced in obtaining the consumer's agreement.

Mr. E. W. Hill: I support Mr. Fawssett in his opinion that it is fallacious to assume that high-tension metering necessarily measures accurately the losses of a power transformer. With current-transformer characteristics as they are, and with the limitations on the ampere-turns of high-tension current transformers and the consequent large and rapidly-changing phase-angle error at very low roads, one can only speculate as to the magnitude of the inaccuracies involved in measuring the iron losses on the high-tension side, when they form the only load. As regards Mr. Dransfield's instance of a consumer who had to pay 1s. per unit at a time of very light load, the high-tension meter on that installation may have been very seriously over-registering the iron losses by reason of phase-angle errors in the current transformer as much as 10° to 15° in advance of the proper angle. If the losses are measured by a specially compensated meter on the low-tension side, the uncertainty as to accuracy disappears and a very close approximation to the truth can be attained by imparting to a meter (which has a good straight curve as part of the necessary right initial characteristics) the required shunt running effect for the iron losses, combined with a series creep for the copper losses. It is not very difficult to contrive this especially as modern power transformers have quite low iron losses and thus do not involve too exaggerated a forward shunt creep. It would almost seem that the separate iron- and copper-loss integrators were unnecessary, unless it is thought desirable to segregate the record of the losses and preserve the main meter's record unimpaired as an "accurate," or rather an "unfalsified" instrument, and unless the difficulty as to maximum demand becomes involved. The particular difficulty in this respect when more than one power transformer is involved apparently makes unavoidable the use of separate iron- and copper-loss meters, with some kind of mechanical summation. In my opinion the suggestion of adopting electrical summation of two or more compensated meters is unsound, since it is necessary not to summate currents (strictly watt components of currents), but dial readings of the individual meters, which have an arbitrary and non-systematic relation to the currents in the meter coils. The measurement of kVA demand is a very difficult problem, and I should shrink from using the author's solution of that problem unless no other were available. The conditions which would compel the use of the method outlined in the paper are such as would in general arise only where an understanding consumer was concerned. Obviously the case quoted by the author is one of bulk supply to a small township, where there will be a resident engineer who will be receptive to the necessary technical explanations. There are two details of the paper on which I wish to comment. First, I do not agree with the statement on page 510 that the iron losses vary with the cube of the voltage: my experience is that they vary rather as the square of the voltage. Secondly, under the heading "Maximum Demand in kW" (Appendix 1) there is an item "R.M.S. value of copper losses = 7·02 kW." I have always understood that power should be expressed as an arithmetical average and not as an R.M.S. value, and I therefore cannot see why the author should express the copper losses in this way.*

Mr. J. G. Wellings: I do not agree that an instrument transformer is necessarily a possible source of danger on high-tension lines. It has been proved that instrument transformers can nowadays be made as reliable as most other parts of the circuit. On the other hand, from the point of view of price, there are certain cases—particularly above 33 kV—where some such scheme as the author advocates is possibly justified. Current transformers can be installed in perfect safety at a reasonable cost on any high-voltage line, provided a bar-primary construction is adopted. As regards minimum current for bar-primary transformer ratings, a rough rule is that for circuits above 33 kV the full-load primary rating in amperes which it is possible to meter with reasonable accuracy corresponds approximately to the rating of the circuit in kV; i.e. for 66 kV, 66 amperes can be metered satisfactorily; for 132 kV, 132 amperes, etc. I should like to emphasize that in any case where the current is less than these values there is a decided advantage in using current transformers on the low-

* Revised for the *Journal*.

tension side, in order to avoid the possibility of trouble under short-circuit conditions. Alternatively to the author's scheme, I would refer to the various methods of employing instrument transformers on the low-voltage side and compensating for the drop on the power transformer in the manner described in a recent paper.* Apart from cost and technical considerations, the questions of maintenance and space are important in regard to high-voltage instrument transformers. While I think there is a good deal of scope for the author's arrangement for the metering of circuits of 33 kV and above, for voltages below 33 kV a direct metering scheme is preferable. I agree with both the previous speakers who have criticized the statement that the core loss of the power transformer varies with the cube of the voltage. The loss actually varies roughly as the square of the voltage, and I feel that the author's figures in this connection are erroneous.

Mr. F. E. J. Ockenden: I am interested in Mr. Fawssett's results obtained by direct measurement on a transformer, which show that the iron losses vary very nearly as the square of the voltage. According to a paper by Webb,† a remarkable diversity of opinion exists as to what the Steinmetz formula for iron losses really amounts to at transformer densities. The paper quotes Stroud as saying that the index is 1·7 up to 17 000 lines per cm^2, while Prof. Bailey gives the figure as 2·4 between 14 000 and 18 000 lines per cm^2. Barrett, Brown, and Hadfield give it as 2·1 from 12 000 to 17 000 lines per cm^2, and Wilde says it does not exceed 2 up to 15 000 lines per cm^2. The average figures given by Webb are 1·9 for 12 500 lines per cm^2 and 2·5 for 15 000 lines per cm^2. Assuming as correct the author's statement that a satisfactory density would be in the region of 13 000 to 13 500 lines per cm^2, the index would be 2. This not only confirms Mr. Fawssett's figures but also shows that the author is probably in error in stating the index to be anything like so high as 3. On the other hand, assuming that the value 2 is correct, the meter with which he proposes to measure these losses becomes even more accurate than he suggests. As far as I can see, the only objection to it as an accurate means of measuring the iron losses is that we must either put it across the primary terminals of the transformer, which may mean making it suitable for extremely high voltages, or across the secondary terminals, in which case the transformer regulation has to be taken into account. Since the chief purpose of his meter is to measure losses due to fluxes, I suggest that we should connect its voltage winding directly to a tertiary winding placed on some point in the transformer which is approximately at earth potential. The arrangement then becomes a core-loss meter operated directly by the flux in the transformer core. It should be quite feasible to put such a tertiary winding on a power transformer, since similar windings are now used for measurement purposes on X-ray transformers operating at 300 000 volts. Treated as a copper-loss meter, the device shown in Fig. 1 omits the resistance in the secondary circuit which is essential if an adequate phase displacement between the two fluxes is to be obtained. By suitably proportioning the ratio between the resistance and the reactance of this circuit it is possible to make the torque on the disc due to the operation of the two fluxes almost proportional to the value of the resistance. I think this feature provides us with a ready means of improving the performance of the meter. The author points out that the transformer losses vary with temperature and that the suggested meter takes no account of such variations. If, however, the series resistance in the secondary circuit were constructed of copper and were placed either within the transformer tank, where it would attain a temperature proportional to the temperature of the transformer itself, or in proximity to a heater device carrying a current proportional to the load current, the resistance of the secondary would vary with the temperature of the transformer and the torque would vary in the same manner. The meter would then register the copper losses correctly, independently of the temperature of the transformer windings.

Mr. W. A. H. Parker: Although previous speakers have raised objections to the complications which will arise if the equipment advocated by the author is installed, the fact that the transformer losses on a bulk supply vary between 1·47 and 7·25 per cent (see page 508) makes it important to have a method of measuring these losses which is not based on guesswork. There is a danger in so-called simplification; we ought to realize that if the losses are not directly measured there is a tendency for the seller to assess them at too high a figure when fixing his prices. Further, when, in the near future, we are all purchasing from the Central Electricity Board, we shall be interested to know whether the Board propose to measure the losses or to assess them at an extra 5 or 10 per cent and add these figures to our bills. It is impossible to estimate transformer losses, because they vary with the running conditions of supply. I should like to refer here to a problem which I have discussed with a large number of people and to which no one seems to know the answer. Section 51 of the 7th Schedule of the 1926 Act says: "The number of kW of maximum demand for any month shall be deemed to be twice the largest number of units of electricity supplied to the undertakers during *any* consecutive 30 minutes during that month." The Merz system of maximum-demand recording does not fulfil these conditions, and so far as I am aware there is not on the market an indicator or recorder depending on integration which does fulfil them. It seems to me that some form of thermal device will have to be used to meet these requirements. Thus at present we are not really complying with the Act, and I therefore think that meter engineers should apply themselves to this particular point as quickly as possible. This sentence was probably drafted in error in the Act, but it would be interesting to know whether those responsible for drafting it approached any representative of the electrical industry before the wording was decided upon. It was rather interesting to note the reactions of the meter manufacturers to the original inquiry which we sent out in connection with the special equipment required for the metering system dealt with by the author. Only two of the firms approached were really interested; the others either ignored our suggestions or put forward alternatives which we had

* J. G. Wellings and C. G. Mayo: "Instrument Transformers," *Journal I.E.E.*, 1930, vol. 68, p. 704.

† *Journal I.E.E.*, 1926, vol. 64, p. 409.

already turned down. I believe, however, that the meter manufacturers have now realized that their previous conservative attitude was wrong, and we must admire the work they have done in connection with the Central Electricity Board. The author makes it quite clear (page 514) that he does not consider this to be the best method to adopt for metering all e.h.t. supplies, but he puts it forward as an improvement on the present method of metering such supplies on the secondary side of step-down transformers.

Mr. R. S. J. Spilsbury: The instruments proposed by the author have one definite advantage over the alternatives which have been suggested in the discussion, in that they leave the main meter unaffected. This may be important where a certificate from an independent authority is desired: such an authority would presumably refuse to certify a meter which had been so sophisticated as to include the losses of the supply transformer, but if the author's instruments were used the main meter would be of the normal kWh type, and certifiable as such, while the accuracy of the iron-loss and copper-loss meters would be less important. The instruments would also give interesting information as to the relative importance of the iron and copper losses of the transformer under the conditions of use. The author's value for the exponent of the total-loss equation has been generally criticized, and while values of 3 and over are not unknown, they are, I think, unusual in transformers of normal design. A new distribution transformer which I recently tested gave a value for the exponent of almost exactly 2. If, however, a meter giving a speed proportional to (voltage)^3 is required, and if the possibility of constructing a satisfactory meter for (voltage)^2 is admitted, the result might be attained by a method similar to that used for the voltage compensation of the Hill-Shotter kVA maximum-demand indicator. Here a small electromagnet, energized from the voltage circuit, controls the position of a shading loop working in the air-gap of the driving electromagnet, and so varies the speed of the meter that at constant current it is proportional to the voltage, over a certain range. If the speed of the author's meter were already proportional to V^2, it could presumably be made proportional to V^3 by this method.

Mr. A. J. Gibbons: In my opinion, up to 33 kV metering should be done on the high-tension side. When iron losses of the low order referred to in the paper and by preceding speakers are in question, I doubt whether the loss in revenue caused by high-tension meters failing to register the iron losses for the short periods when the power transformers are completely off load really amounts to very much in the long run. With regard to the safety of the instrument transformers, I think that bushing-type current transformers should be quite as reliable as oil-switch bushings, line insulators, or the cables, and with compensated or mumetal cores very good performance can be obtained with bar-primary current transformers at quite low full-load currents. In this connection I should like to refer to some current transformers which are being installed in some 66-kV armour-clad switchgear at one of my company's stations on circuits with a full-load rating of 45 amperes. Bar-primary current transformers with ratio 60/1 amperes have been satisfactorily produced by the switchgear contractors, giving Class B accuracy at the rated secondary burden. Potential transformers are perhaps not so reliable as current transformers. For the more usual commercial voltages, therefore, I am in favour of metering on the high-tension side. Where this is impossible, one has to think of some method of dealing with the iron and copper losses. As regards the compensated meter described by Mr. Fawssett, to measure the iron losses correctly the meter would have to creep at about 1/200th or less of full load, and it seems doubtful whether its performance would be at all consistent. For this reason I prefer the meter described by the author: it rotates at a reasonable speed and should be capable of satisfactory and consistent running. I am surprised at the author's suggestion that the iron losses vary as E^3, as it is current practice on all the transformer test-beds with which I am acquainted to correct iron-loss measurements to the rated voltage by means of the square law. The third-power law arrived at by the author may result from the fact that he has employed rather higher flux densities than are commonly met with. As regards the temperature corrections referred to in the paper, the copper losses of a transformer are made up of two parts, namely the I^2R losses, which increase with the temperature, and the stray losses due to eddy currents in the windings and adjacent iron, which decrease with a rise in temperature. These temperature corrections are relatively unimportant, because in any case the percentage copper losses are small. It has occurred to me that the author's copper-loss meter could readily be fitted with automatic temperature compensation by providing a shunt to the meter coil which could be situated in a pocket in the transformer top oil; by suitable choice of the temperature coefficient of the shunt it would be easy to arrange for the correct excess current to be forced through the copper-loss meter as the temperature of the transformer, and therefore of the shunt, increased. I have made a number of detailed calculations in one or two cases where the meters were placed on the wrong side of the transformers, and the registrations had to be corrected for transformer losses. Unless far too large a transformer has been installed for the load, I have found that the variations in the corrections to the maximum demand in kW, and to the kWh, are comparatively small over a wide range of maximum demand and load factor. In most cases I have found it perfectly feasible on bulk supplies to come to an agreement as to the loss corrections which is fair and satisfactory to both parties, and I suggest that the above procedure is simpler, and certainly cheaper, than the elaborate scheme put forward by the author.

Mr. C. L. Lipman: I shall confine my remarks to the design of the instrument illustrated in Fig. 1. Whilst I agree that the electromagnetic arrangement is equivalent to a quadrature transformer by virtue of the various air-gaps provided in its magnetic circuit, I fear that the use of a movement of this construction may give rise to a low efficiency. It will be interesting to know, therefore, whether such an instrument has actually been constructed, and, if so, what are its operating characteristics, energy consumption, and driving torque at the normal rating.

Mr. D. Sclar: The iron-loss meter is shown as a transformer, and if the speed of the rotor is to be proportional to E^2, the flux must also be roughly so. Regarding it as a power transformer, this means that the flux increases as the square of the load on the transformer, which, of course, is not the case. Again, although the flux due to the voltage coil increases in direct proportion to the voltage, this creates a current in the secondary winding proportional to the voltage; so that one effect cancels the other and we are left with only the magnetizing current. It should not be very difficult to make a meter for measuring E^2. Some of the previous speakers have suggested that this could be done by placing resistance in the secondary coil; it should also be quite easy to make the meter by having resistance external to the meter connected across the current coil, so that the current in this coil would be proportional to the voltage. A certain potential difference across this resistance would be taken to the current coil, and the result would be an E^2 effect. With such a system a standard meter having a special current coil would be sufficient for the purpose. I am interested in the author's suggestions as to cost: the table shown in Appendix 3 is not a very happy choice, because at 33 kV the difference in cost of the two systems is not very marked. For the direct metering the price is £516, as compared with £514 for the indirect system, and of course the latter is much the more complicated arrangement. If the first alternative is adopted it would appear to be necessary to calculate the maximum demand due to copper losses, to obtain the maximum demand due to iron losses by reading these from the recording voltmeter, and then to add these vectorially to the true kVA demand—a laborious process. It would also be necessary to have some sort of chart recorder on the kW indicator, to ensure that the maximum kVA and the maximum kW were registered at the same time, as otherwise the average power factor could not be found from the maximum-demand indicators on the kW and kVA sections. One system of metering on the low-tension side and getting results fairly accurately for the high-tension is to install current transformers on the primary side but take the pressure from the power transformer itself. It could not be taken direct in the case the author shows, as the pressure is 11 000 volts, but a potential transformer could be used. The main cost of a high-tension equipment is that of the potential transformers, which are much more expensive than current transformers. If the cost of a potential transformer for 11 000 volts is taken as 1, for 33 000 volts the approximate price is 4, and for 66 000 volts about 12; whereas in the case of a current transformer, taking the price of 11 000 volts as 1, for 33 000 volts it would be 2, for 44 000 volts 3, for 66 000 volts 4, and for 88 000 volts 5. Not only does the cost of a potential transformer rise much more rapidly as the primary voltage increases, but it is an expensive instrument even at 11 000 volts. As for installing current transformers on the primary side and taking pressure from the secondary side of the main power transformer, even in the case of the star-delta type this can be done by a system of cross connection. The regulation of a power transformer is not very good (3 to 6 per cent), and one might think that the voltage on the meters would be reduced by this amount. Although this is in fact the case, it must be kept in mind that the primary and secondary voltages differ in phase. As a matter of fact, this phase difference compensates for the iron losses of the transformer, and the results obtained by using high-tension current transformers and no potential transformers (taking the voltage from the main transformer) gives one the high-tension input less the copper losses. The copper losses can be measured by an I^2R meter. According to the paper, however, the highest copper loss is just under 70 000 units, about 0·5 to 0·6 per cent of the total output—and this under the worst conditions where the full load of one transformer is on. When the full load is taken from two transformers these copper-loss figures are halved, so that even if one neglects the copper losses an error of only about $\frac{1}{2}$ per cent is introduced.

Mr. S. H. C. Morton (*in reply*): The discussion has been characterized by the general criticism of the figure in the paper for the variation of iron losses of a transformer, with pressure. The assumption that the losses vary as E^2 is based mainly on the fact that on transformer test-beds it is still customary to use this figure. The actual index depends on the flux density at which the transformer is run, and Fig. A shows this point clearly. This curve, which has been prepared by the manufacturers of the iron, is for plates of the usual thickness used for transformer cores, and on examination it can be seen that the losses vary with the pressure in the following manner:—

B (lines per cm^2)	Losses proportional to
10 000 to 11 000	$E^{1·9}$
11 000 to 12 000	$E^{2·4}$
12 000 to 12 500	$E^{2·5}$
12 500 to 13 000	$E^{2·6}$
13 000 to 13 500	$E^{2·9}$
13 500 to 14 000	$E^{3·1}$
14 000 to 14 500	$E^{3·4}$

The density at which a transformer core is run will vary with different transformers, but a value of 13 500 lines per cm^2 is quite normal.

Several speakers have mentioned the fact that, with the metering equipment on the primary side of a transformer, the errors in the measurement of iron losses will be large when no secondary load is being taken. This is, of course, true, and, if the periods of no load are long, quite large errors can occur in the meter registrations. In these circumstances it would probably be better to install the metering equipment on the secondary side of the transformer and make provision for the measurement of the losses.

The compensated watt-hour meter has been discussed at some length. Although in certain cases it may be quite a useful instrument, it is subject to many disadvantages. I agree with Mr. Fawssett that the pressure creep and current creep of this meter would, theoretically, vary as E^2 and I^2, and my remark on the first page of the advance copies of the paper was

intended to convey the fact that the number of transformers on excitation had no effect on the meter. The wording has been altered for the *Journal* to make this point clear. When considering the pressure creep (to compensate for iron losses) of this type of meter, it must be remembered that it would be from 1·0 per cent to 0·5 per cent, or even less, of the meter's full load, and in my opinion would be rather unreliable.

The main use of the compensated meter would be for the measurement of a supply with only one transformer and a maximum-demand charge based on kW. The special calibration fee for the compensated meter is given by Mr. Fawssett as £10, whereas a copper- and iron-loss meter, including calibration, can be purchased for £3 10s. The compensated meter would indicate

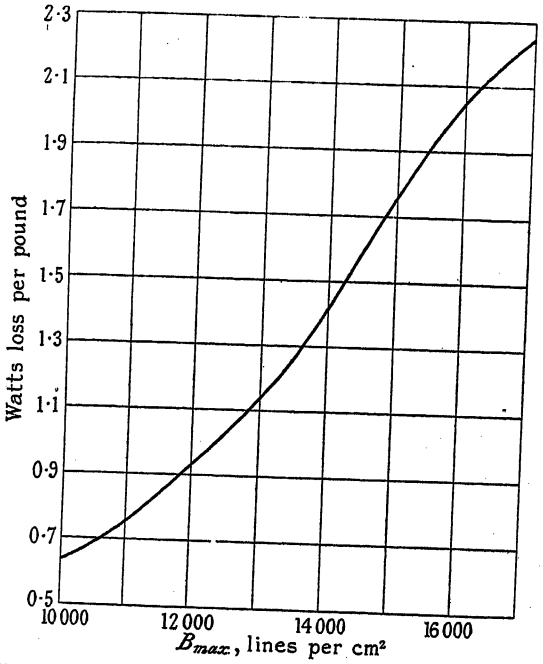


FIG. A.—Stalloy loss at various inductions (0·014 in. stalloy) and 50 frequency.

the kW demand, whereas this would have to be calculated if separate loss meters were employed. The calculation would be quite simple if the secondary demand were known.

I agree with Mr. Hill that if a supply were given to two transformers and compensated meters were used in the manner suggested by Mr. Fawssett no account of the maximum demand due to losses would be given on the summation meter. The same result would be obtained by using separate loss meters, and the cost of the equipment would be lower.

Regarding the loss meters, Fig. 1 was not intended to show the design of these instruments but was included to illustrate the principles on which the instruments would operate. Copper- and iron-loss meters have been manufactured which have made use of the standard single-phase watt-hour meter, and the only alteration has been to the coils. In the case of the iron-loss meter, a standard shunt coil for the correct voltage is fitted and a coil with a large number of turns is wound on the series electromagnet. In series with the latter is an external resistance. The electrical connections are shown in Fig. B.

The copper-loss meter is made in a similar manner, except that a standard series coil is used and the non-inductive resistance is internal.

The iron-loss meter errors are about ± 1·0 per cent from 50 to 150 per cent of normal pressure. The error introduced by a variation of 10 per cent over, to 10 per cent under, normal frequency is approximately 1·5 per cent.

The copper-loss meter can be so adjusted that the errors are within ± 2·5 per cent from full load to about $\frac{1}{10}$ load, i.e. from full load to 25 per cent of full load of the transformer, the losses of which the instrument is measuring. Beyond this point the errors increase. This meter is also susceptible to frequency variation, and tests taken with a frequency 10 per cent above normal caused the meter speed to increase about 8 per cent. With a frequency 10 per cent below normal the meter speed decreased 8 per cent.

Both Mr. Ockenden and Mr. Gibbons suggest a method of compensating the copper-loss meter for the temperature of the transformer winding. Although it would be possible to improve the performance of the instrument by methods on the lines suggested, I do not think the slight improvement effected would be worth the expense.

Mr. Fawssett suggests a slightly higher temperature of the transformer windings than that given on page 512. I think the temperature should be estimated for each

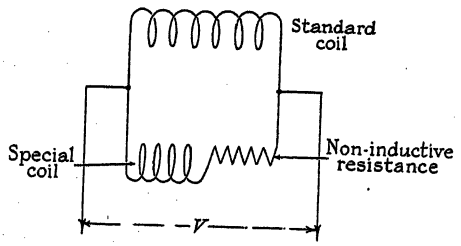


FIG. B.

particular supply when the approximate conditions are known.

The suggestion made by Mr. Ockenden to have a tertiary winding on the power transformer as a means of feeding the iron-loss meter is very useful, although, unless the losses varied as E^2, the accuracy of the meter registrations would not be so high as if the meter were fed from the secondary pressure. This is indicated by Figs. 2 and 4 in the paper. An iron-loss meter designed on the lines mentioned by Mr. Spilsbury (i.e. a special compensating device to make the meter register in accordance with E^3), in conjunction with the tertiary winding, would provide a very accurate means of integrating iron losses.

The calculation of the kVA maximum demand has also been generally criticized. Mr. Hill and Mr. Dransfield are of the opinion that the method is rather too complicated to explain to the non-technical consumer, and Mr. Sclar thinks the calculation itself too laborious. The calculation is perhaps slightly complicated, but

more in the preparation from the transformer test-figures than in the actual work that has to be carried out before each account is presented. The routine work at the end of each period for which an account is presented is quite straightforward. This can be seen in Appendix 2. Mr. Dransfield's suggestion to add a suitable amount to cover the difference between primary and secondary kVA does not go sufficiently far, as he brings forward no means of assessing the amount to be added. In this matter I agree with Mr. Parker that the only method of estimating the primary kVA that is fair to both the supplier and the consumer is one in which all the available facts are taken into consideration. A calculation based on the facts is the only means by which these conditions are fulfilled.

I cannot agree with Mr. Fawssett that technical and financial considerations never allow the metering to be done on the incoming supply side. In most cases where the supply is afforded by means of underground cable, and the pressure does not exceed 11 000 volts, I would consider the incoming side the correct place to install the metering equipment. Mr. Fawssett does not think that the problem dealt with in the paper is representative of the general type of supply with which a power supply authority has to deal, and in this I agree with him. The equipment has been considered with a view to metering large bulk supplies, and I think that the figures given indicate this point clearly. For smaller supplies a modified form of the equipment suggested could very conveniently be installed.

Mr. Dransfield thinks that the integration of iron losses at times of low load would lead to misunderstanding and dispute between the consumer and supplier. I consider this point of view to be quite wrong. If a consumer uses the supply in an inefficient manner it should not be necessary for the supply authority to pay for his losses. At the same time I think the consumer should be given such advice as will enable him to keep his losses, both electrical and mechanical, as low as possible.

Mr. Dransfield appears to have misunderstood my meaning in regard to the recording of primary switching operations. I think that, in practice, it would be perfectly safe to assume that no transformer would be excited unnecessarily at the time of maximum load if iron losses were being measured. This assumption would make switching records unnecessary for the purpose of calculating the primary kVA maximum demand.

I cannot agree that the main meter errors would be as great as the transformer losses. With an average transformer working at full load with a load factor of 100 per cent, the losses would be in the region of 2 per cent of the load. This is very much greater than the error of a modern meter. In addition, it is not good practice to neglect to measure transformer losses because of inherent errors in the main meters.

I agree with Mr. Hill that the expression " R.M.S. kW " in Appendix 1 in the advance copies of the paper should have been " average kW." This has been revised for the *Journal*.

Mr. Wellings's remarks on instrument transformers for use on e.h.t. lines are very interesting; it is useful to have figures at which current transformers with bar primaries will operate in a satisfactory manner. Whilst I agree with Mr. Wellings that instrument transformers on e.h.t. lines are probably as reliable as most other parts of the circuit, I think that they are much more likely to break down than instrument transformers connected in the secondary circuit of a power transformer.

In reply to Mr. Spilsbury, I agree that any complications in a metering equipment such as those which would be introduced by the measuring of copper and iron losses should be made outside the main meters, and that all instruments should be standard and carry out a simple duty.

The suggestion made by Mr. Spilsbury to include a voltage-compensating device in the iron-loss meter in order to make its speed proportional to E^3 would be very useful if used in the manner mentioned earlier. If, however, the instrument were connected to the secondary side of the transformer its speed would vary in proportion to the iron losses with a variation of supply pressure, but its registrations would be very greatly affected by transformer regulation, which would not affect the actual iron losses. With the E^2 meter a fall of primary pressure causes a positive error in the meter, and this has a tendency to cancel the effect due to transformer regulation.

Mr. Gibbons's statement that, up to 33 kV, metering should be done on the incoming side is, in my opinion, too general. In practice, although the pressure has a large bearing on the position in which the equipment should be installed, it is also necessary to consider load factor, the maximum load, the basis on which maximum demand (kW or kVA) is charged, and other factors, before a decision is reached. Mr. Gibbons remarks that the variations in the corrections to the kWh and maximum demand in kW to obtain primary input from secondary output are comparatively small over a wide range of maximum demand and load factor, unless the transformer is too large. In the majority of supplies, however, it is usual to have two transformers, one of which is on load and the other used as a spare. The spare transformer is usually kept warm by being left connected to the high-pressure bars, unless the iron losses are measured. Under these circumstances the losses could amount to a large percentage of the kWh measured by means of meters connected in the secondary circuit. The ratio of losses to secondary kWh would also be affected by load factor.

Regarding Mr. Sclar's remarks on kVA maximum demand, all the recording instruments necesssary to obtain either simultaneous secondary kVA and kW, or secondary kW and power factor, have been included in Appendix 3. The calculation to obtain primary maximum demand in kVA is also fully explained in Appendix 2.

Mr. Sclar suggests a method of obtaining input units less copper losses by means of current transformers connected to the incoming supply side and potential transformers connected to the secondary side of the power transformer, the reduction of pressure due to transformer regulation being compensated for by the difference in phase angle between the primary and reversed secondary pressures. It is of course true that

the reversed secondary pressure lags behind the primary supply pressure by an amount depending on the transformer design and the power factor of the circuit, and with most lagging power factors this angle helps to compensate for the losses. This is not so, however, when the circuit power-factor is leading, the angle between the reversed secondary pressure and the primary current then being greater than that between the incoming pressure and current. The method, therefore, would leave some doubt as to the actual proportion of the primary supply being registered, and, in addition, would give no means of assessing the primary kVA.

DISCUSSION ON

"THE GROWTH OF ELECTRICAL MEASUREMENT FROM ITS COMMENCEMENT."*

SCOTTISH CENTRE, AT EDINBURGH, 15TH DECEMBER, 1931.

Mr. A. F. Stevenson: The accuracy of electrical measuring instruments 40 years ago was very low, as I found when engaged in calibrating commercial meters and voltmeters in the middle 'nineties. The instruments then being made had soft-iron movements involving a very considerable hysteresis error. They were calibrated by means of a degree scale, first on a rising current and then on a falling current, and when the readings were plotted a "hysteresis" diagram was obtained. A mid-way line was taken, and it was found that measurements made on a rising current were about 2 per cent low, whereas those on a falling current were about 2 per cent high. Since then I have seen someone attempting to read to ½ ampere from a 100-ampere instrument of this type! The Kelvin electrostatic voltmeter and ampere balance were the first instruments to give reliable readings. The author's high opinion of the value of remote control gear is not shared by maintenance engineers. It would have added to the interest of the paper if the author had indicated some of the troubles associated with the working of such apparatus.

Mr. J. Eccles: I should like to correct the figure of 60 per cent on page 42 of the paper as the ratio between the heat energy of the steam and the total energy in the coal. Fortunately for the industry, this figure is usually of the order of 80 per cent and often it is higher. I appreciate, however, the author's remarks with regard to the necessity of accurate measurement in the boiler house. In the local power station we have a remote-indicating kW meter in every boiler house (four in all), so that it is not necessary for the firemen to travel to a central point in order to ascertain the load. These have been found to be amongst the most valuable instruments in the station, as they help the firemen to maintain the correct steam pressure and temperature, especially over the period of peak load. As regards repeaters, the Midworth type seem to be soundly constructed, apart from the fact that the main contacts appear to make and break slowly, which might give rise to arcing. I should like to ask the author whether trouble of this kind is likely to be serious. I am particularly interested in the American device for the transmission of remote signals by means of phase-shifters, because we have recently employed this method with success to obtain remote indication of a wind vane. A single-phase rotor is employed, thus reducing the number of interconnecting leads to two. The author's remarks with regard to power measurement are of great interest, and in this connection I should be glad to know whether the method evolved by Mr. Fawssett has been extensively employed in commercial undertakings. Turning to the instrument for measuring earth resistance, described on page 41, does not this device measure impedance rather than resistance? Since alternating current of variable frequency and possibly poor wave-form is employed, the reading should, I think, depend on the inductance as well as the resistance of the circuit. A very important subject scarcely touched upon in the paper is the measurement of maximum demands. One of the most pressing needs of the supply industry is a reliable and cheap instrument to measure maximum demand, of both kW and kVA. I should be glad if the author would briefly describe any improvements which have been made of recent years in this class of instrument.

Mr. A. Mears: Has anything been done in the way of transmitting the readings of instruments over great distances by means of the photo-electric cell? With regard to the question of contacts mentioned by Mr. Eccles, the difficulty might possibly be overcome by having magnetic contacts so that when the contact was made the arm would hold on firmly and when contact was broken it would spring away rapidly. In the early part of the paper the author attributes the Foucault principle of a damping disc to the late Prof. Ayrton: I had always thought, however, that this formed part of the original Hookham patent for the first d.c. meter.

Mr. G. Gunn: In the first place, I should like to confirm Mr. Eccles's statement about the 60 per cent boiler efficiency mentioned in the paper. Secondly, I would appeal for closer co-operation between instrument makers and power station engineers. When bad readings are obtained it is usually found that the instrument and

* Paper by Mr. F. C. KNOWLES (see vol. 70, page 36).

not the plant has gone wrong. The investigation of cases of instrument error involves great loss of time and labour. In many cases instruments could be improved if they were submitted to the power station engineer before being put on the market. Many instruments which operate satisfactorily in the laboratory prove to be of little value under service conditions in the boiler house, where they are subject to rough usage and dirty conditions.

Mr. L. B. Torond: The paper makes no mention of the transformer load indicator employing the principles of the dial-type thermometer and current transformer. Can the author give the views of instrument makers on this subject?

Prof. G. W. O. Howe: I am pleased to see that the author refers to the pioneer work of the late Prof. Ayrton, with whom I had the good fortune to be associated during the closing years of his life. Accuracy of measurement is only a relative term: an accuracy to within 1 or 2 per cent, which the author quotes as being quite satisfactory in some of the instruments described, would be considered very poor in other electrical measurements. Enormous advances have been made during the last 20 or 30 years in measurement, especially electrical measurement of a high degree of accuracy. I am interested in the author's references to geophysical applications. Many universities are now considering the institution of courses in geophysics, a subject which involves a knowledge of many branches of physics. It is one of the marvels of modern science that electrical methods are being used at the present time for finding out both what is in the earth beneath and what is in the heavens above.

[The author's reply to this discussion will be found on page 529].

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 4TH JANUARY, 1932.

Mr. H. E. Dance: The author deals chiefly with the remote reproduction of measurements obtained by known methods. The removal of the control room from the actual centre of activity appears to be the natural line of progress. The human body offers the most obvious example of this. The Midworth repeater appears to have great possibilities, because it enables any kind of measurement to be translated into a current which is proportional to the measurement, and it also enables the currents so obtained to be compounded in a variety of ways. It seems to be capable of almost unlimited application, provided that it can be supplied at a reasonable cost. I understand that the method of transmitting movement by means of induction motors which are connected in parallel to a single supply, with their rotors also in parallel, has an important application in the control of the various recording devices employed in the manufacture of sound films. In such apparatus it is, of course, necessary to keep all the parts in exact synchronism. The possibility of applying thermo-couples is limited to kVA indication. It is impossible to integrate the quantity by this means, because the torque of the instrument is proportional to $(kVA)^2$. Any method of kVA measurement which does not lend itself to accurate integration has practically no commercial value. I should be glad of more information about the method of measurement shown in Fig. 6. This is the only one I have come across which holds any promise of success in fulfilling all the functions of kVA measurement at a reasonable price. What are its limitations, and what is its accuracy when employed in combination with commercial meters and instrument transformers? My opinion of the arrangement shown in Fig. 6 is based on the fact that I find it difficult to regard the volt-ampere as other than a scalar quantity, which does not admit of negative values. No instrument which can rotate in either direction depending on the phase angle of the circuit can truly measure kVA. Fig. 6 appears to be satisfactory in this respect. Fig. 8 is of great importance, and it teaches us a lesson with regard to voltage distribution. It is commonly assumed that mere earthing will secure safety from electrical shock. Too little attention is given to potential gradients. There is no doubt but that in the near future voltages up to 6 000 volts will be employed in this country for large movable machinery, e.g. dock machinery, and mining and quarrying plant. When such voltages are employed more than ordinary care has to be taken in the matter of earthing. As regards future requirements in metering equipment, we badly need a meter which will indicate in January what the maximum demand is likely to be in the following 12 months. Such a meter would be a boon to many consumers who find the strictly logical application of a 2-part tariff not altogether satisfying to their commercial instincts.

Mr. G. E. Barrett: The author directs attention to the application by the Central Electricity Board of the principles of remote indication. Can he tell us what quantities and values are to be indicated, and the distances over which such indications are to be transmitted? Centralized indications for a large transmission system would obviously be advantageous to the control engineer from many points of view, although presumably there is a definite commercial limit to what can be done. I should like to know the percentage accuracy of the instruments indicating such values as steam pressure, total load on the station, and voltage. I realize, of course, that these are not instruments of precision, and that high accuracy is not required in ordinary commercial operation. In Fig. 6 the author gives a symbol for metallic rectifiers; is this the symbol suggested by the British Standards Institution? Figs. 6 and 8 are inconsistent in that respect. The data given in Fig. 8 are of particular interest to all concerned with the earthing of structures. It does, however, appear that the shells of equal resistance bear some definite relation to the type of structure or spike in use. Can the author give an explanation of the characteristic curves shown? The figures given on page 42 for the efficiency of steam-raising plant are too low, even when judged by the standards of several years ago. I feel, therefore, that the work of manufacturers and operating staffs should be credited with

greater achievements than the author apparently has in mind.

Mr. T. R. Rayner: The author mentions that it is necessary to make considerable modifications in the systems employed for remote meter reading when the Post Office lines are utilized, and I should like to refer to one of the special conditions met with under these circumstances. When the attenuation to voice frequencies exceeds a certain value it is necessary to insert valve repeaters in order to obtain satisfactory telephony. For reasons of economy it is essential to obtain the meter readings over the telephone channel, and this necessitates the use of voice-frequency currents. In an amplified line it is not feasible to rely on the strength of the received current for the indication, as a slight variation in the gain of the repeater would falsify the results. One way of overcoming this difficulty is to cause a power receiver of the type described by the author to drive an impulser which sends one impulse to line for unit load at the instrument. At the receiving end a ratchet device moves a pointer over a suitably graduated scale. Two different frequencies are employed, one for increase and the other for decrease of load. This arrangement works very satisfactorily, but has the disadvantage of being slow if a large number of instruments are involved. It is usual to employ only one power receiver for any number of initiating instruments, and this is required to return to zero before each reading. A much more rapid method is obtained by arranging a row of contacts under the pointer of the initiating instrument and arranging for the pointer, which normally rides free, to be depressed on to the contacts at the instant the meter reading is required. The number of the " marked " contact controls the line impulses. This is a very simple and rapid arrangement capable of giving 17 meter readings and up to 200 circuit indications in approximately 20 seconds. An accuracy of 1 per cent can be readily obtained, but $2\frac{1}{2}$ per cent is generally regarded as sufficient.

Prof. E. W. Marchant: I should like first to say something about the remarks at the beginning of the paper on the work of the late Prof. Ayrton. I had a good deal to do with him in the early days, and we had some of the very first direct-reading instruments that were made. When Prof. Ayrton was in Japan, he and Prof. Perry got to work on the making of an energy meter, and they devised a " clock meter." Taking an ordinary 8-day clock, they put a coil on the pendulum which carried a current proportional to the p.d., and arranged another coil underneath which carried the mains current: the change in the rate of swing of the pendulum gave an indication of the power which was used, and the gain of the clock was proportional to the energy consumed. This is one of the most accurate types of meters that are available to-day. I am interested in the Midworth repeater because many years ago we wanted to devise a regulator to maintain a constant pressure in connection with some lamp tests. We built up a dynamometer with an arm moving between two contacts. The trouble was that these contacts had a tendency to stick. I should like to know how that difficulty has been overcome in the Midworth repeater. The way we got over it was to use the same device as was employed in the Brown cable relay, i.e. we allowed the arm to rest on a rotating drum, thus eliminating the friction between them. With regard to earth-plate resistances, we made a number of tests on these some years ago. It is well known that the resistance to earth lies almost entirely in that part of the ground which immediately surrounds the earth plate. It depends mainly on the size and shape of the electrodes, and, for homogeneous ground, is proportional to the specific resistance of the ground material. We found that earth resistance depends more on moisture than on anything else. Carbon monoxide indicators are being used in the Mersey Tunnel, and the readings obtained from such instruments are of great importance. In this connection I should like to give a word of warning to users of motor-cars. I am informed that if a motor-car engine is run for 3 minutes in an ordinary garage with the door closed, the air becomes dangerously poisonous due to carbon monoxide. Finally, the author refers to measurements of conductivity in " reciprocal megohms " per cm^3; why not call these units " gem mhos "?

Mr. G. A. Burns: With regard to the problem of transmitting indications over a distance, this is generally accompanied by a request for economy in pilot wires, and with impulsing equipment used either as Mr. Rayner described or in conjunction with Midworth equipment, several indications can be transmitted simultaneously over a single pair of wires. For instance, we might simultaneously transmit readings of amperes, volts, and kilowatts, by using different transmitting frequencies for each reading, these frequencies being sorted out at the receiving end to operate their respective indicating instruments.

Mr. H. H. Harrison: I am glad to note the author's references to the early work of Ayrton and Perry, and I hope that in due course we shall have an Institution address on the work of these two men. With regard to Figs. 1 and 2, there is a fundamental limitation to which this scheme is subject. It is a constant-current arrangement only so long as there is no leakage between the conductors. The coded impulse method of transmitting indications involves no limitation as to distance or the type of conductor to be used. The scheme shown in Fig. 3 is also subject to a fundamental objection. It may be described as a " start-stop " method. When key G is operated the apparatus at that end starts up at once, but line and apparatus lags intervene before the apparatus at the other end of the line starts up, the result being that when the two pointers are moving they will be a little out of phase. Whether or not this phase difference is serious, depends entirely on the distance between the two sets of apparatus. The 3-phase scheme shown by one of the slides is very old, and what are described as " order " telegraphs have been made on these lines. The advantages of the impulse method are that its range is practically unlimited and almost any physical quantity can be transmitted in terms of the movement of a pointer, can be coded into pulses, and accurately shown on the type of indicator exhibited by the author.

[The author's reply to this discussion will be found on page 529].

WESTERN CENTRE, AT CHELTENHAM, 8TH FEBRUARY, 1932.

Mr. W. A. H. Parker: I am very interested in the author's remarks in connection with long-distance transmission of indication. A large number of such schemes as water-pumping stations and reservoirs would employ such methods if arrangements could be made to avoid the cost of the connecting lines; perhaps in the future some method depending upon radio impulses could be used. The scheme put forward for the measurement of kVA is interesting, but I should like to know whether the metal rectifiers would be stable over a number of years, because it is a comparatively short time since this type of rectifier was put on the market and we have not yet had sufficient experience of its stability. As regards the use of alarms to give notice of approaching peak loads, we have used an overload relay of the single-phase type in connection with kVA demand on consumers' premises. We find, however, that having once operated the relay the current has to be considerably reduced before the operating arm will return to its original position, and to avoid this we have inserted a switch across the operating coil so that it can be short-circuited by the attendant directly the load has been reduced. We engineers engaged in the electricity supply industry should ourselves use electrical methods of indication so as to be able to speak from experience when discussing similar propositions with consumers.

Mr. H. B. Eccles: I am interested in the question of motor-operated instruments, and I should like to ask the author whether any such system of control has been applied to frequency meters so as to give a quicker and more definite movement to this type of instrument. Recently a number of queries have been put to me concerning the true accuracy of frequency meters. Power station engineers desire such instruments to have larger scales with more accurate and definite indication. No doubt this desire springs from the demand for steady control of frequency, now that electric clocks are being used.

Mr. W. F. Cooper: The question of remote indication of loads and other important data is of serious concern to the engineer in these days of rapidly expanding networks and loads. The section of the paper dealing with earth plates is very useful. The general tendency is to bury earth plates and forget them, but with the increasing use of discriminating relays a regular routine of substation earth-plate testing has become very necessary.

Mr. T. A. B. Gatley: I have met with cases where different ohmic values obtained on the same earth connection caused anxiety as to whether the setting of earth-fault protective gear was altered in consequence. Tests taken on the relays proved, however, that their sensitivity was not affected with varying values of between 2 and 7 ohms for the earthing resistance.

Mr. S. B. Haslam: Can the author supply a reason why so few of the Ayrton ohmmeters were made? I should have thought that an instrument of this type brought out in 1881 would have created a big demand. Turning to the problems of remote indication and control, the author states that the Midworth system operates on direct current. Is it also possible to operate this system by means of alternating current, and can it be adapted to give remote integration as well as remote indication? The system illustrated in Fig. 3 is known as "tally-metering" and it would appear that it has been designed to give occasional "spot" readings on demand, in contrast to the Midworth system which provides a continuous indication on a record. I believe that the tally-meter now incorporates a "tallygraph," but I am not quite sure whether this does more than record the "spot" readings. I should like to know whether this latter system has been put into operation, and, if so, with what results. The system would appear to have some uses for selective metering in association with remote control schemes. With regard to earth testing, the author described an instrument for determining the specific resistance of the ground which should be a great help to engineers when determining the best position for earth plates; it also appears to have a big field of use in connection with geophysical surveying. The instrument should enable us to locate water at a considerable depth, and in this connection I should be glad to know to what depth it will give reasonably accurate results and what degree of variation in specific resistance it will register. Is it possible by this means to locate coal and to trace or find a seam of coal which has been lost through a fault? The use of electrical indicating, measuring, and recording instruments in the boiler house is becoming more general, and I am glad that the author stresses the advantage to be gained from the warnings which will be given. Intelligent use of such instruments as water-purity meters, CO_2 recorders, etc., will enable the necessary repairs to be carried out in time to avoid a shutdown. In connection with indication of leaky condenser tubes, what proportion of cooling water leaking into the condensate would be registered on a water-purity meter?

Mr. R. W. Biles: What is the distance limit of the remote indicating systems described in the paper? What are the general accuracy limits aimed at, and is it necessary for the devices to be calibrated on site? Indications at distances of about 200 miles from the point of measurement are likely to be required. If repeater systems are employed, would they not introduce considerable errors? It is anticipated that indication and control work will be carried on over two wires, and presumably it is mainly a question of using a suitable battery of relays for this purpose. The author's reference to earth-plate testing (see Figs. 7 and 8) is of considerable interest. A number of tests which have been conducted upon towers and earth pipes show that in a sandy clay soil the combined resistances of towers and pipes vary between 0·75 and 3 ohms. The figures for towers vary between 0·83 and 3·2 ohms, and for pipes between 0·82 and 6·5 ohms, the values for pipes always being the higher. In a rocky shale type of soil the resistance of the tower may vary between 6 and over 300 ohms. A few tests taken on the same towers at 2- to 3- monthly intervals show in some cases a rise in resistance, and in others a slight fall. In all cases the

differences are negligible for practical purposes. More of these tests will be conducted as opportunity permits. It has been possible to establish the rise in the curve when the potential spike approaches the current spike. For instance, in one particular case a potential spike was placed 55 ft. from the tower under test, and the current spike at 75 ft. and 150 ft. The readings for the respective current-spike positions were 10 ohms and 5·6 ohms, showing an error of nearly 100 per cent, and demonstrating the importance of working on the flat portion of the curve in Fig. 7. The downward trend of the curve has not been established when the potential spike is placed close to the tower under test, and the flat portion of the curve is not as truly flat as indicated, but shows a small increment. It is recommended that the current spike should be placed a considerable distance from the object under test, and it would appear that errors might be introduced due to the inductance of the long leads employed. There is already a correction figure for the resistances of the leads and spikes, and as the instrument is of the a.c. type some further correction would be necessary for the inductance. Reference has also been made to the advantage of using the earth-plate tester to determine the most suitable position for the earth plate; in the case of substations this can be exploited without much difficulty, but with towers the limited amount of space available gives very little scope for this procedure. Tests have also been made comparing the 3-point method with the direct method, and difficulty is experienced in making the results agree. If the 3-point method is used, there are many cases in which an instrument having a full-scale deflection of 1 500 or 3 000 ohms is necessary, so that the resistance between spikes can always be ascertained. This is frequently above 300 ohms. The 3-point method has the greater advantage of eliminating errors due to leads and spike resistances, but it also has the disadvantage that, if the object resistance is low and the spike resistance high, unavoidable errors of observation in the readings will give an unreliable result.

Mr. S. H. C. Morton: The measurement of kVA is of great importance, and it is gratifying to know that experiments are being carried out in order to obtain an instrument capable of indicating this quantity with higher accuracy than is at present possible. The present instruments enable kVA measurements to be made with a fair degree of accuracy, provided the current and voltage waves are sinusoidal, but when one or both waves contain harmonics kVA measurement appears to be impossible. The distorted wave-form I have in mind is that produced when a mercury-arc rectifier is in the circuit. The voltage curve appears to be a pure sine wave, whilst the current curve contains fifth and seventh harmonics of the order of 15 and 10 per cent respectively of the fundamental. I should like to ask the author whether he could suggest any method which could be employed to measure the kVA of a circuit of the type mentioned.

Mr. T. Stretton: I am surprised that no one has yet questioned the author regarding the measurement of high voltages of the order of 132 kV. Apparatus for measurements of this kind is very expensive, and I should welcome any information regarding inexpensive but efficient types of apparatus for this purpose. In this connection I understand that Prof. Thornton has devised a comparatively simple and cheap instrument called the "ionic wind voltmeter."* As regards the use of platinum wire in connection with CO_2 apparatus, I find that platinum has the disadvantage that it burns away rather quickly in the presence of various gases. I should like to know whether the author can give particulars of an alloy of platinum which will withstand a higher temperature than pure platinum.

* See *Journal I.E.E.*, 1931, vol. 69, p. 533.

The Author's Reply to the Discussions at Edinburgh, Liverpool, and Cheltenham.

Mr. F. C. Knowles (*in reply*): Reference has been made in the discussion to the various systems of remote indication. In this country there has been very little experience of such systems over a period of years, but with the extensive experience which will be available during the next few years owing to the adoption of remote indication by the Central Electricity Board, considerable information will doubtless be available. Those who are not only designers but users of such equipment will be glad to have comparative information.

Mr. J. Eccles asks whether the method evolved by Mr. Fawssett has been extensively employed in commercial undertakings. So far as my experience goes, it is not extensively employed in this country, but in Canada and the United States the thermo-couple system is in use in some large undertakings.

While Mr. Mears's suggestion about magnetic contact may be intriguing, it does not appear to be very practical, as those who have had experience with the breaking of magnetic circuits will appreciate.

In reply to Mr. Barrett respecting the quantities, values, and distances over which indications are transmitted, under the Central Electricity Board in general the quantities are megawatts, megavars, and voltage. In some particular cases other quantities may be required. The distances of transmission vary considerably from a matter of a few miles to nearly 200 miles. For these long distances transmission is over Post Office lines through repeater stations, and thus an impulse or audio-frequency link has to be employed.

Prof. Marchant asks how the tendency of contacts to stick was overcome in the Midworth repeater. It should be remembered that these contacts operate a motor which, while having a very efficient brake, has a certain amount of inertia, and is so arranged that after the contact is broken the motor makes a few revolutions, thus causing the contacts to clear one another definitely. In practice it is very interesting to watch the operation of these contacts; the moving contact nearly always floats midway between the two other contacts.

Mr. Harrison, remarking on Figs. 1 and 2, raises the question of the effect of leakage between the conductors. The amount of leakage available before causing an appreciable error depends upon the voltage applied and the

conditions of service and the sensitivity of the apparatus. As an example, if the full-scale deflection for the receiver were 20 mA and the voltage applied to the line were 50 V, if a value of leakage were allowable which would not cause an error greater than 1 per cent, which would be equal to a leakage current of 0·2 mA, then the resistance of this leak would be 25 000 ohms. This would of course be a very low value indeed. The majority of lines are maintained to at least 1 megohm, 40 times this value, which means that in practice the maximum error due to leakage is not 1/40th of 1 per cent.

The various systems described by Mr. Rayner and referred to by Mr. Burns are quite interesting developments of the application of automatic telephony to position indication. The application of the various methods will be followed with much interest.

Mr. Haslam, in comparing the Tallymeter system with the Midworth system, refers to the fact that the Midworth system provides a continuous indication or may be applied to a chart recording instrument to give a continuous log of the variations of any quantity, and asks whether the Tallymeter system can be similarly applied. This latter system is only a recent development, and while it appears that it would be possible by introducing further complications in the way of a follow-up system to give continuous indication, it would be necessary from time to time to revert back to zero so as to insure that there were no additive errors.

Many speakers have referred to the measurement of earth resistance, and the information given by Mr. Biles is extremely valuable. He states that it has been possible to establish the rise in the curve when the potential spike approaches the current spike, and gives some figures for a case when the current spike was placed at a distance of 75 to 150 ft. from the tower. It has been found that for an earthed structure such a tower, particularly when it is of low resistance, the current spike has to be placed at a distance of 300 ft. or more from the tower in order to obtain a flat portion of the resistance curve. From theoretical considerations the so-called flat portion of the curve is not truly flat but shows a slight increase in resistance, but if the separation between the spikes and the earth connection under test is correctly chosen, the centre portion of the curve will be flat enough for all practical purposes. The inductance in the leads to the spikes has no effect whatever on the readings of the instrument, although the latter employs alternating current for the test. It will be appreciated that such an inductance would be of quite small value and is in series with a high ohmic resistance. Mention is made of the correction factor for the resistance of the leads and spikes, but it is when the potential spike exceeds a certain definite high value that this correction factor has to be applied, and in general the correction is quite small. With regard to the use of the Perry earth tester for determining the most suitable position for an earth plate, it is quite understandable that with towers the amount of space available is not sufficient to enable measurement of the specific resistance of the soil to be made. It is, however, a simple matter to drive spikes of given dimensions into the earth at several points and to compare the resistances of these spikes as a means of indicating the most suitable location.

Mr. Biles also mentions comparative tests which have been made using the 3-point method and the direct method, and says that difficulty is experienced in making the results agree. This is quite understandable as in the 3-point method the resistances with the two auxiliary earths which are necessary are included in the measurement, and the unavoidable observational errors which are mentioned will give unreliable results. The direct method, in which the resistance of the auxiliary spikes only has an indirect effect on the results, is not only much more satisfactory but more rapid and extremely simple.

Reference has been made by some speakers to the effect of the ohmic resistance of earth connections causing variations in the operation of earth-fault protective gear. This is becoming increasingly appreciated, and many erratic operations of relays are now being explained by the unexpected high resistance of the earth plate now that facilities are available for easy and accurate measurement.

Both Prof. Howe and Mr. Haslam refer to the application of earth-resistance measuring instruments to geophysical problems. While work in this respect has been going on for the past three or four years the whole science is so new that it is not possible to say more than that some very promising results have been obtained in the location of faults in strata and metallic veins, but a great deal more work will have to be done in order that the effect of the many variables which go to make the result may be understood. In many ways it is one of the most promising applications of electrical measurement to geophysical problems.

It was expected that a certain amount of interest would be occasioned by the scheme of kVA measurement put forward with the use of metal rectifier. It is quite true that metal rectifiers are a recent innovation, but very extensive development has been going on and an increasing confidence is being felt in their use. It should be remembered that while they might not yet be suitable for use with substandard instruments, instruments having first-grade accuracy are being made up daily with metallic rectifiers and are on the whole giving complete satisfaction. The theory of the application of metal rectifiers to kVA measurement is too long to be included in this reply, but it will be published separately.

In response to Mr. Dance's question as to the accuracy of such arrangement, it appears from tests that have been carried out that it is within ± 2 per cent, to which of course would be added or subtracted the errors of any transformers which might be used.

I agree with Mr. Dance in regarding voltamperes as a scalar quantity, which does not admit of negative values; kVA must always be positive, and thus the statement that no instrument which can rotate in either direction depending on the phase angle of the circuit can truly measure the kVA is an important one.

The applications of instruments to the mechanical side of electrical plant have been referred to by several speakers, and I have to thank Mr. J. Eccles for his correction of the statement (in the copies of the paper distributed at the meeting) that the ratio between the heat energy of the steam and the total energy of the coal is more of the order of 80 per cent than 60 per cent.

The use of impurity indicators for the boiler feed or condensate is becoming more and more necessary, especially in view of the continually increasing pressure. In some of the latest plants it is the practice to extract and condense samples of steam before passing over to the turbines so that the carry-over may be tested and a check kept on it to prevent erosion, etc., of the turbine blades. For this purpose there are several instruments available, both of the portable type and the continuous indicating and recording type.

MODERN TRAMWAY ROLLING STOCK.*

By E. R. L. FITZPAYNE, B.Sc., Graduate.

(ABSTRACT *of paper read before the* SCOTTISH STUDENTS' SECTION, *at* EDINBURGH, *2nd December*, 1930.)

In modernizing tramways, engineers have had three main objects in view, viz. increased speed, quiet running, and comfort. Increased speed does not imply that the car should have a speed of, say, 40 m.p.h., but it means that by braking and accelerating it should be able to maintain a good average speed. At present the braking is good, but the acceleration might with advantage be improved. The acceleration from 15 to 25 m.p.h. is very poor compared with the acceleration from rest to 12 m.p.h.

The drive from the motor to the axle has undergone important developments. By having the motor totally sprung-borne, noise and wear on the track are lessened. One method of achieving this is by the worm-driven motor. The motor itself is of standard design, except that a worm is cast on the end of the armature shaft. The worm-wheel is mounted on a " quill," and the drive from the quill to the axle is taken through a flexible coupling—the most interesting feature of this motor. It is an alternative to the more orthodox cardan-shaft drive. Helical gears with a $7\frac{1}{2}°$ angle have also been used with success in place of the spur gearing. The fact that the teeth are always in contact ensures that there is no jarring as with spur gearing, with the result that noise and vibration are materially reduced.

In all tramways the operation of new rolling stock is hampered by the old. As it would not be economical to scrap the old rolling stock, means have to be devised to bring it up to date as far as possible. On the Edinburgh system there are a large number of cars equipped with 40-h.p. motors, and it is a problem to run these on routes where cars with 50-h.p. motors are running. In order to increase the speed of the 40-h.p. motors the field turns were reduced, but this experiment failed as the cars would not climb the hills satisfactorily. An alteration of the gear ratio from 61/14 to 57/18 has been tried; this, of course, has necessitated reductions and re-stepping of the resistances, causing the motors to take a greatly increased starting current. This procedure considerably shortens the life of the motors and is therefore unsatisfactory. Experiments have been made with a weak-field attachment, which shunts each of the fields by a non-inductive resistance when the controller is in the full parallel position. A series relay prevents the field contactors closing should the current in the motor be too large to make field-weakening practicable. In another method which has been employed the 40-h.p. motors are re-wound with Class " B " insulation and the fields are weakened so that the motors actually develop 75 h.p. Two cars have been fitted with these motors, and their speed on the gradients has proved very satisfactory.

The magnetic track brake is undoubtedly harmful to the motors: modern practice combines the magnetic brake with the air brake. Thus the first notch of braking will be pneumatic only, and the remaining notches pneumatic and magnetic. If the rheostatic brake could be substituted for the magnetic brake, the track brake could be operated by air, and the track shoes might then be made of some softer material than the cast steel used at present. This would reduce the wear on the track and at the same time the rails might be made of harder non-magnetic steel, which would have a longer life. Owing to the bad riding of trucks at the higher speeds the flanges on the tyres wear badly, and hence Grade X 70- to 80-ton tyres are being used. When new, these tyres make bad contact with the rails; it is some time before they wear down to the shape of the rails, and this seriously affects the track brakes.

The bow collector is a big improvement on the trolley, and is almost a necessity where high speeds are attained.

Another improvement is the use of light-weight alloys in the construction of cars. Aluminium alloys are coming into prominence for this purpose on account of their lightness, and, in the case of a magnesium alloy known as " Elektron," the saving in weight per wheel set amounted to 24 per cent. These alloys are manufactured in the " annealed " or " heat-treated " condition, according to the tensile strength required.

Interesting trials have lately been made with cars equipped for regenerative control. Compound motors are used with the shunt fields connected in parallel across the line. Regeneration is obtained by strengthening the shunt field: this raises the e.m.f. of the motor and causes energy to be returned to the line.

* A Student's Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

A.C. RECTIFICATION FOR POWER PURPOSES.*

By R. MACWHIRTER, B.Sc., Associate Member.

(ABSTRACT *of Paper read before the* SCOTTISH STUDENTS' SECTION, *at* GLASGOW, 10*th December*, 1930.)

SUMMARY.

The object of the present paper is a brief review of the physical principles, field of service, and characteristics, of different types of rectifiers. Rectification in radio circuits, and mechanical rectifiers (including the jet-wave rectifier), are excluded.

MERCURY-ARC RECTIFIERS.

There are three kinds of conduction of electricity through gases—spark conduction, glow discharge, and arc conduction—all of which can be used in rectifiers. The essential condition for rectification is that only one of the electrodes shall be capable of emitting electrons and this requirement may be met in various ways. As only the arc will carry heavy currents, however,

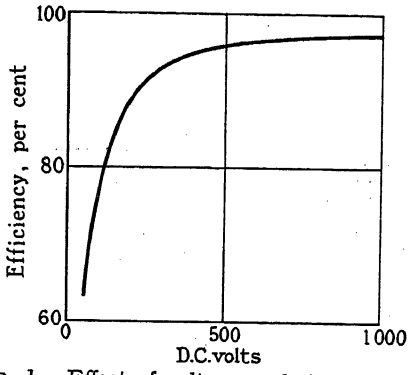


FIG. 1.—Effect of voltage on bulb efficiency of mercury-arc rectifier.

devices depending on spark and glow conduction are ignored.

A tube using mercury and iron or carbon as electrodes shows extremely good rectifying properties. In such tubes the white-hot "cathode spot" is the source of electrons and of conducting mercury vapour, and with mercury as the negative pole the arc is self-supporting.

In the practical rectifier (of glass up to about 125 kW capacity, and of steel up to 5 000 kW capacity) the vacuum is about 0·01 mm when cold, reaching 0·3 mm in operation. Glass bulbs are cheap and have a very long life, especially in intermittent operation: a life of 30 000 hours has been known. Steel-cased rectifiers with asbestos-packed and mercury-sealed joints have pumps permanently connected and controlled by automatic pressure-gauge starters. The arc is struck by auxiliary anodes excited from a low-voltage a.c. source.

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Efficiency.—The losses in the arc are roughly proportional to the current, as the voltage drop (of the order of 25 volts) is practically constant. The mercury-arc rectifier is thus primarily a high-current, high-voltage device (see Fig. 1), and even at 600 volts it compares

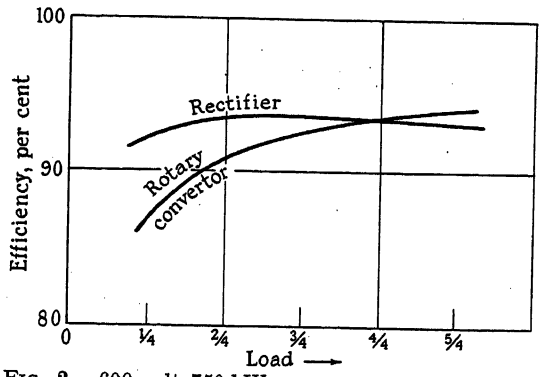


FIG. 2.—600-volt 750-kW mercury-arc rectifier and rotary-convertor units compared.

favourably with the rotary convertor. Further, its efficiency is well maintained at low loads. Fig. 2 represents a typical comparison.

Reliability.—Modern vacuum seals and anode design result in few back-starting difficulties. Sudden short

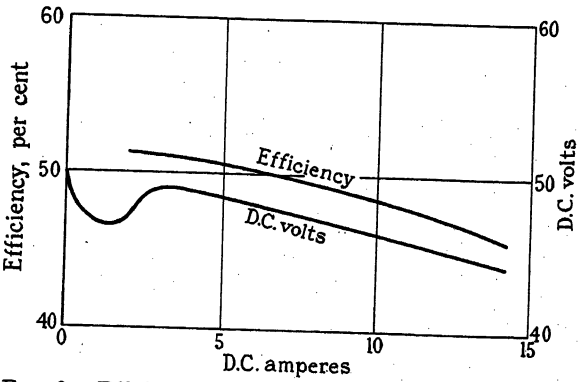


FIG. 3.—Efficiency and regulation of 50-volt 12-ampere Tungar rectifier.

overloads give no trouble, but prolonged overloads cause heating of the anodes, which conduces to back-starting. Overloads of 100 to 200 per cent for 5 minutes, and 20 per cent for 2 hours, are practicable.

THERMIONIC RECTIFIERS.

For rectification at low voltages the gas-filled bulb (e.g. the Tungar type) competes with the mercury

arc. In this pattern a glass bulb filled with argon gas to a pressure of several centimetres contains a tungsten filament and a carbon anode. The filament emission

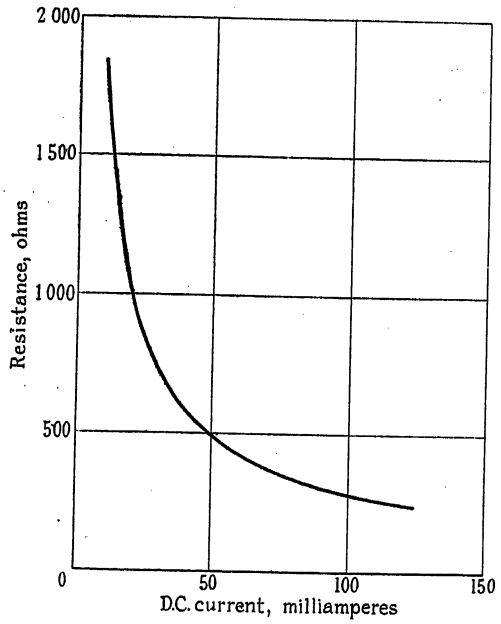


FIG. 4.—Copper-oxide rectifier: variation of "forward" resistance with current. (The variation is partly due to temperature changes.)

causes ionization by collision within the gaseous argon, and, given suitable electrode spacing, gas pressure, etc., the discharge is intensified into an arc. Such valves are made for pressures up to 75 volts and currents up to 36 amperes. They may be single- or bi-phase. The

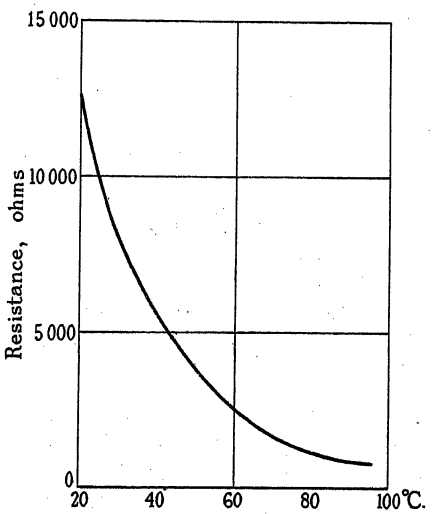


FIG. 5.—Copper-oxide rectifier: variation of "reverse" resistance with temperature.

filament is heated by means of a low-voltage transformer tapping. Starting is simple.

Efficiency.—Besides the voltage drop in the arc (about 4 volts) there is the filament-heating loss—about 30 watts in a 6-ampere bulb. The full-load efficiency of a large installation (90/80 amperes, 28/38 volts) reaches 80 per cent: 390 watts are dissipated in the filaments. For smaller installations a reasonable working efficiency is 55 per cent (see Fig. 3).

The average life of a Tungar bulb is of the order of 1 000 to 2 000 hours, the life being approximately inversely proportional to the load.

Pure thermionic rectifiers differ from the Tungar type in that conduction from filament to plate takes

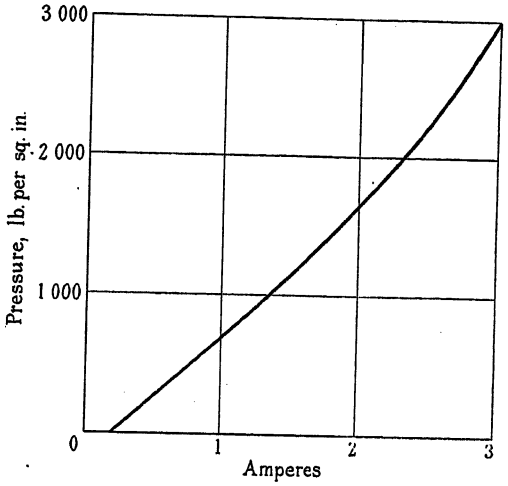


FIG. 6.—Copper-oxide rectifier: variation of "forward" conductivity with pressure at constant voltage.*

place through a very high vacuum. Ionization by collision is therefore negligible, and the current stream is entirely electronic.

THE COPPER-OXIDE RECTIFIER.

Grondahl discovered that a copper disc heated to about 1 000° C. in air exhibits marked rectifying properties. Investigation showed the seat of the valve action to be

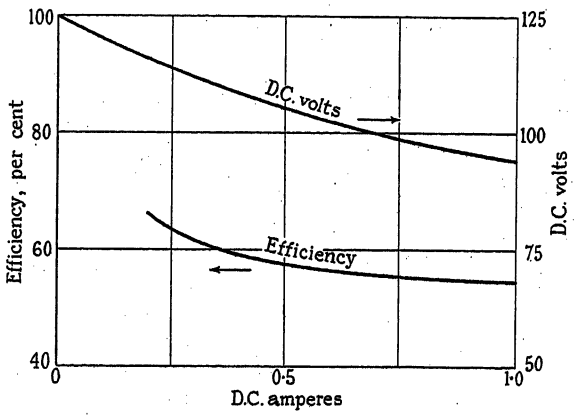


FIG. 7.—Efficiency and regulation of 110-volt 0·75-ampere copper-oxide rectifier.

at the copper-and-oxide junction; the ratio of resistances in opposite directions is of the order of 1 000:1, and approaches 10 000:1 in especially good specimens.

* I. R. SMITH: "Actual Characteristics and Applications of the Copper-Oxide Rectifier in Practice," *Electrical Times*, 1930, vol. 78, p. 976.

Research has shown that the oxide layer consists of cuprous oxide near the copper and cupric oxide near the surface. Cuprous oxide falls in the class of semi-insulator, and cupric oxide in the class of semi-conductor; so that if a plate of (say) lead be pressed into contact with the oxide, we have the equivalent of a leaky condenser with a " graded " dielectric whose plates are the lead plate and the copper base. It would appear that the rectifying action results from the distribution of dielectric forces being sufficient to attract electrons across one of the oxide boundaries when the lead is positive with respect to the copper, but not when the potential difference is reversed. The practical rectifier consists of a number of units assembled under pressure in series or parallel in such a way as to meet the voltage and current requirements. The current rating is about 0·3 ampere per sq. in., and the voltage rating 3 to 4 volts per unit.

Characteristic curves of a copper-oxide rectifier are given in Figs. 4, 5, and 6. It will be seen that the voltage/current relation is not linear; that the resistances (forward and reverse) fall with temperature, and that within limits the conductivity increases with the pressure.

For a general-purpose battery-charging set rated at 0·8 kW a working efficiency of 50 to 55 per cent is claimed by the makers. The regulation and efficiency curves of a 110-volt 0·75-ampere rectifier are shown in Fig. 7. These units have a long life, the makers claiming only 3 to 4 per cent reduction of efficiency over a life of 20 000 hours.

Electrolytic Rectifiers.

In actual fact these rectifiers are not electrolytic in action, but are the equivalent of a leaky condenser with unsymmetrical dielectric.

If a " formed " plate of aluminium and another of lead are immersed in a solution of ammonium phosphate, the combination shows imperfect rectifying properties, the direction of conduction being from lead to aluminium. The formed plate shows a thin, tenacious layer of oxide, to which a layer of oxygen, evolved during formation, adheres.

The maximum useful output voltage is definitely below 100 volts, for the following reasons: (*a*) to enable it to stand up to high voltages the electrolyte must be diluted, with consequent increase in resistance; (*b*) the electrolytic rectifier is also an electrolytic condenser, and above 100 volts heavy charging currents flow.

Owing to these characteristics and imperfect rectification, the maximum efficiency of electrolytic rectifiers is only about 30 per cent. Their only advantage is low initial cost.

The above table, based on that given by Guntherschulze,* summarizes the fields of service of different types of rectifiers.

Voltage	Current in amperes			
	0·1	1	10	100 and upwards
10	Copper oxide	Copper oxide Tungar Electrolytic	Tungar Copper oxide	Rotary convertor
100	Copper oxide Thermionic valve	Copper oxide Tungar	Mercury arc Tungar Copper oxide	Rotary convertor Mercury arc
500	Copper oxide Thermionic valve	Copper oxide Mercury arc	Mercury arc	Mercury arc Rotary convertor
1 000 and upwards	Thermionic valve	Thermionic valve Mercury arc		

* "Electric Rectifiers and Valves."

THE DEVELOPMENT OF THE LONDON AUTOMATIC TELEPHONE SYSTEM.*

By M. G. HOLMES, B.Sc.(Eng.), Student, and L. F. SALTER, B.Sc.(Eng.).

(ABSTRACT *of paper read before the* LONDON STUDENTS' SECTION *8th May*, 1931.)

A review of the development and traffic characteristics of the London telephone area some 10 years ago established the fact that an automatic system was economically justified. This having been determined, it was necessary to ascertain which of the many systems would be best suited to deal with the London telephone traffic, in which a very large proportion of calls are completed over junctions. This factor calls for a system in which the junctions are not inflexibly associated with the numbering scheme: it was therefore decided to adopt the Strowger or " step-by-step " director system.

Under the manual system, in order to obviate the necessity for junctions from each exchange to every other exchange in the area, certain exchanges were selected as junction lending centres. The completion of certain calls necessitated routing via these centres, and as a result transmission was not always satisfactory. The idea of a tandem exchange to act as a junction centre had been conceived previously, and the introduction of automatic working into London proved to be a convenient opportunity for the adoption of this system of junction lending. A central exchange to which were laid heavy-gauge conductor cables, loaded and unloaded, was thus available, and systematic control of transmission and junction traffic routing therefore became possible. In order that this exchange might fit in with the automatic scheme arrangements were made for the use of automatic switches.

To enable subscribers connected to automatic exchanges to obtain connection to manual and automatic subscribers without adopting different dialling procedures, it was necessary to install " call indicator " equipment at the manual exchanges. Key-sending apparatus was fitted in the automatic exchanges for the completion of calls passed over order wires from manual exchanges. This type of apparatus was also installed in the tandem exchange to cater for calls from the manual exchanges to be passed via the automatic switches to automatic exchanges and the " call indicator " positions in manual exchanges.

The main feature of the " director " system is, as its name implies, the director. This piece of apparatus gives flexibility in junction routing by translating the exchange-code digits into other selected digits enabling maximum economy in switches and junction line plant to be effected. Subscribers' circuits in the external cables are connected to one side of a main distribution frame, the final selector multiples are connected to the other side, and connection between the two is made by means of " jumpers." Different ranks of switches are connected by permanent cables, and cross connections between junctions and apparatus are carried out on an intermediate distribution frame, the object being to facilitate redistribution of circuits on which changes are comparatively frequent.

Estimates are made of the quantity and destination of the traffic which it is anticipated will be originated by the subscribers on an exchange, and these figures are used as a basis of design for the exchange. The number of each type of switch can then be calculated by means of Erlang's theory in the case of " full availability " groups, and modifications of it in the case of " graded " groups, grading being the means adopted to ensure that each switch is used to a maximum extent compatible with a reasonable grade of service. Grading between ranks of switches is carried out on special link frames. Traffic records to ascertain the traffic actually passing in the exchanges are taken periodically, and modifications to the number of switches and junctions are made on the basis of these records.

The basic feature of the maintenance of London automatic exchanges is a system of periodic routine testing. Switches, relay sets, etc., are tested regularly by means of automatic testers known as " routiners." The tests made simulate actual calls in principle, but impose more severe conditions. In this way faults are anticipated instead of being allowed to develop later.

Each portion of the London area is kept under review as regards anticipated development, and not less than five years before a new exchange is required economic studies of the area involved are made and a site as near as possible to the theoretical economic centre is purchased. The size of site necessary is determined from accommodation data based on a study of anticipated conditions 30 years after the exchange opens. The building is then erected, and the equipment contractor installs the apparatus to the Post Office Engineering Department's specification. All parties concerned in the progress of the work are regularly advised by a system of progress reports, and by this means delays are largely avoided. Numerous detailed tests are carried out on the apparatus before the exchange is put into service, the final one being that in which actual traffic conditions are simulated.

Since the commencement of the programme for the conversion of the London exchanges to automatic working, endeavours have continuously been made to devise a method of working whereby the number of operators involved in a call from a manual exchange to an automatic exchange may be reduced. Various schemes for

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

the completion of the call by the manual operator without the assistance of a key-sender "B" operator have been tried experimentally, and a system of key-sending from the manual exchange by the use of four voice-frequency currents operating tuned relays in the automatic exchanges which has been used successfully under working conditions is being installed throughout the London area.

The present trend of apparatus development is in the direction of minimizing the quantity and value of apparatus held during a call; common apparatus is used to set up the call and is then released. Economies in line plant will be effected by extensions of the tandem system of working to particular portions of the London area, and sub-tandem exchanges are being installed. As the conversion of the London area to automatic working proceeds, more and more of the semi-automatic plant in the tandem exchange will become spare. The idea has been mooted of working large groups of junctions from provincial centres via this exchange, thus enabling still more calls to be completed by means of automatic switches.

ASPECTS OF THE TRANSMISSION AND RECEPTION OF STILL PICTURES.*

By C. J. F. Tweed, Associate Member.

(Abstract *of paper read before the* London Students' Section 13*th March*, 1931.)

It is intended, in this paper, to give an outline of the fundamental principles involved in the majority of picture systems, then to deal with the application of these principles to one or two definite systems, and finally to point out some of the uses of such systems and the difficulties involved in their application.

Fundamental Principles.

The three essential points to be considered are:—

(*a*) The conversion of the picture at the transmitter into electrical impulses.

(*b*) The re-conversion of these impulses into a picture at the receiver.

(*c*) A means of performing operations (*a*) and (*b*) synchronously and in phase.

(*a*) The first process is usually accomplished by wrapping the picture round a cylinder which is traversed by a scanning point. In order to explore the whole picture area, motion in two planes is necessary. One motion is generally obtained by revolving the cylinder, or the scanning point, or both; and the other by traversing the scanning point in a direction at right angles to the drum rotation by means of a lead screw or similar device. The actual path traced out by the scanning point on the surface of the drum is therefore a spiral one, similar to the threads on a screw. The distance between each adjacent path of the spiral is termed the "mesh" of the picture, and this largely determines the amount of detail obtained. If the picture is specially prepared in such a way that its surface is conducting or non-conducting in sympathy with the intelligence which it is wished to convey, a metal stylus can be used as a scanning point. Although this method has the advantage of simplicity, its use is obviously limited. Perhaps the most usual method is to scan the picture by means of a light spot, and allow the light which is reflected from the surface to modulate a photo-electric cell. If, however, a transparency is used the light will pass straight through the film instead of being reflected; but in this case also the light falling on the photo-electric cell will vary in intensity in accordance with the picture being transmitted.

The particular method used will be largely determined by the amount of detail which it is wished to transmit, and by the operating conditions prevailing. The advantages of several different methods are discussed.

(*b*) In order to render the received signals visible on paper some form of recorder must be employed, and the scanning mechanism associated with this will be somewhat similar to that at the transmitter. Among the kinds of recorders employed in practice are the chemical type and the photographic (or light) type.

In the first, absorbent paper is moistened with a chemical solution and scanned with a metal stylus. Unidirectional current controlled by the received signals is passed through the paper via the stylus and drum, and a mark is produced on the paper due to electro-chemical action. The picture is thus visible immediately, but the speed of working is limited owing to the nature of the recorder.

In the second type of recorder photographic paper or film is used, and some form of light source is therefore necessary. This light source may either be controlled directly by the received signal, as in glow discharge tubes, or else by a light shutter (e.g. Kerr cell and Nicol prisms).

(*c*) In order that any particular picture element on the drum at the transmitter may be recorded at a

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

precisely similar point on the drum at the receiver, the two drums must run synchronously and in phase. This result may be achieved by one or other of the following methods.

(i) The first method makes use of a signal sent out by the transmitter, to control the motion of the drum at the receiver. In some cases this signal consists of a steady tone of short duration which is sent out at every revolution of the drum at the transmitter and is made to control a start-stop mechanism on the drum at the receiver. In other cases a continuous steady frequency is transmitted and used to control the angular motion of the drum at the receiver by means of some form of synchronous machine. This frequency is either sent out over a separate channel or else superimposed on the picture signals.

(ii) The second method makes use of an independent source of constant frequency at each end, and these frequencies control the relative motions of the drums at the transmitter and receiver respectively. A tuning fork, oscillator, or chronometer, is generally used for this purpose, and it should be possible to vary the source at the receiver so as to enable the frequency at the transmitter to be accurately duplicated.

Although method (i) may be simpler and—in some cases—more accurate than (ii), it has several disadvantages. Thus, if synchronism is made dependent on a transmitted signal, its effectiveness will depend on the signal/noise ratio at the receiver. Bad jamming (as in radio reception) or serious fading (as in transatlantic short-wave working) will put the receiver out of step, and time will then be lost in re-synchronizing and re-phasing. Another disadvantage from the point of view of commercial working is that the synchronizing signal occupies an appreciable amount of channel time.

Practical Picture Systems.

A portable picture system which has been designed to work from the air to the ground, or between two mobile ground stations, utilizes independent synchronism and chemical recording. A particular feature of this equipment is that the scanning stylus revolves and the picture drum remains stationary. The message can therefore be observed during reception. Transmission is effected by means of a specially-prepared message form and conducting ink, the ink penetrating a thin insulating surface and making contact with a metallized undercoating. Synchronism is obtained by means of a 1 000-cycle tuning fork at the transmitter and a stable valve oscillator at the receiver, the frequency of the latter being slightly variable so that the fork frequency may be accurately duplicated. Since the picture being received is visible during reception, slight variations in synchronism are immediately obvious and can be corrected by adjusting the oscillator frequency at the receiver. The picture drum is mounted vertically and can be rotated by hand, thus enabling the pictures to be started in phase. The system is intended to send and receive rough sketches, maps, weather charts, and manuscript, with speed and reliability; it is not capable of dealing with half-tone illustrations. The speed of transmission is $4\frac{1}{2}$ minutes for a picture measuring 9 in. × 5 in., the scanning speed being 14 in. per sec.

A second system makes use of optical scanning and a photo-cell at the transmitting end. Independent synchronism is obtained by means of two tuning forks kept at constant temperature in thermostatically-controlled incubators, and a light shutter is used at the recording end. This system has been operated on a transatlantic short-wave radio circuit, and the results obtained show that the speed of transmission is limited owing to the presence of multiple signals.

Applications.

Still-picture transmission is not intended to supersede, or even to compete with, telegraph traffic. It is designed to deal with a different type of matter altogether. Besides the topical pictures which are now familiar features in the daily papers, picture transmission has other important uses. In countries such as Japan or China where the language spoken is not easily interpreted by Morse Code, the transmission of facsimile sheets of manuscript or print is an interesting proposition, while the possibility of reproducing fingerprints, cheques, legal documents, and signatures must not be overlooked.

INSTITUTION NOTES.

National Certificates and Diplomas in Electrical Engineering (England and Wales).

The undermentioned colleges have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (Senior Part-time Course).

Dartford Technical College.
Jarrow Evening Institute.
Lincoln Technical College.
Rotherham College of Technology and Art.

Approved for Higher Grade Certificates (Advanced Part-time Course).

Barrow-in-Furness Technical College.
Cardiff Technical College.
Loughborough College.

Approved for Ordinary Grade Diplomas (Senior Full-time Course).

Hull Municipal Technical College.

Public Works, Roads, and Transport Congress and Exhibition, November, 1933.

The following prizes are offered by the Congress Organizing Committee for papers submitted for discussion at the Congress to be held in November 1933:—

1st Prize—Gold Medal and 100 guineas,
2nd Prize—Silver Medal and 50 guineas,
3rd Prize—Bronze Medal and 20 guineas,
4th Prize—Ten guineas,

with an additional award of 5 guineas for each paper (excluding those to which the above prizes are awarded) selected for discussion at the Congress.

The subject of a paper must be one covered by the objects of the Congress, namely, highways and bridges, water supply, sewerage and sewage disposal, cleansing, gas, electricity, housing and town planning, tramways and light railways, agriculture (small holdings, land drainage, land reclamation, and agricultural education), and local government organization.

Full particulars, together with a list of suggested subjects for papers, can be obtained from the Honorary Secretary of the Congress, 84, Eccleston Square, London, S.W.1, to whom all papers must be sent not later than noon on the 31st December, 1932.

Proceedings of the Wireless Section.

98TH MEETING OF THE WIRELESS SECTION, 23RD MARCH, 1932.

Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 2nd March, 1932, were taken as read and were confirmed and signed.

A paper by Mr. T. L. Eckersley, B.A., B.Sc., entitled "Studies in Radio Transmission" (see page 405), was read and discussed.

The meeting terminated at 7.45 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

99TH MEETING OF THE WIRELESS SECTION, 6TH APRIL, 1932.

Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 23rd March, 1932, were taken as read and were confirmed and signed.

A paper by Mr. B. S. Gossling, M.A., entitled "The Flash-Arc in High-power Valves" (see page 460), was read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the author, which was moved by the chairman and carried with acclamation.

JOINT MEETING OF THE WIRELESS SECTION AND THE METER AND INSTRUMENT SECTION, 8TH APRIL, 1932.

Mr. F. C. Knowles, Chairman of the Meter and Instrument Section, took the chair at 7 p.m.

A paper by Mr. H. R. Harbottle, B.Sc.(Eng.), Associate Member, entitled "Some Acoustic and Telephone Measurements" was read and discussed.

The meeting terminated at 9.25 p.m. with a vote of thanks to the author, which was moved by the chairman and carried with acclamation.

100TH MEETING OF THE WIRELESS SECTION, 25TH MAY, 1932.

Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 6th April, 1932, were taken as read and were confirmed and signed.

The Chairman announced the Council's award of Premiums (see page 144) for papers read before the Section during the session 1931–32.

He also reported that no nominations had been received other than those proposed by the Committee and that the following would therefore take office on the 1st October, 1932:—

Chairman: L. B. Turner, M.A.

Vice-Chairman: Prof. E. Mallett, D.Sc.(Eng.).

Immediate Past Chairman: Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.).

Ordinary Members of Committee: G. W. N. Cobbold, B.Sc., B.A., H. Faulkner, B.Sc., N. Lea, B.Sc., S. H. Long, O.B.E., D.Sc., Prof. J. T. MacGregor-Morris, B. E. G. Mittell, F. Murphy, B.Sc.(Eng.), F. E. Nancarrow, W. J. Picken, E. H. Shaughnessy, O.B.E., G. Shearing, O.B.E., B.Sc., and T. Wadsworth, M.Sc.

Prof. E. V. Appleton, M.A., D.Sc., F.R.S., then delivered a Lecture entitled "Wireless Studies of the Ionosphere."

A vote of thanks to the lecturer, proposed by Lieut.-Col. A. G. Lee, O.B.E., M.C., and seconded by Mr. L. B. Turner, M.A., was carried with acclamation.

The meeting terminated at 7.25 p.m.

Proceedings of the Meter and Instrument Section.

25TH MEETING OF THE METER AND INSTRUMENT SECTION, 5TH FEBRUARY, 1932.

Mr. F. C. Knowles, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 8th January, 1932, were taken as read and were confirmed and signed.

The following papers were read and discussed:—"Recent Developments in Cathode-Ray Oscillographs," by Dr. A. B. Wood (see page 41); "Accuracy of Measurements made with Hot-Filament Cathode-Ray Tubes," by Prof. J. T. MacGregor-Morris, Member, and Mr. H. Wright, B.Sc.(Eng.), Graduate (see page 57).

The meeting terminated at 10.5 p.m. with a vote of thanks to the authors, which was moved by the chairman and carried with acclamation.

26TH MEETING OF THE METER AND INSTRUMENT SECTION, 4TH MARCH, 1932.

Mr. F. C. Knowles, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 5th February, 1932, were taken as read and were confirmed and signed.

A paper by Mr. S. H. C. Morton, Associate Member, entitled "The Metering of E.H.T. Supplies on the Secondary Side of Step-Down Transformers" (see page 507), was read and discussed.

The meeting terminated at 9.45 p.m. with a vote of thanks to the author, which was moved by the chairman and carried with acclamation.

27TH MEETING OF THE METER AND INSTRUMENT SECTION, 18TH MARCH, 1932.

Mr. F. C. Knowles, Chairman of the Section, took the chair at 6.30 p.m.

The minutes of the meeting held on the 4th March, 1932, were taken as read and were confirmed and signed.

An informal discussion took place, the subjects being as follows:—

(1) "Is the British Standard Specification for Meters too Stringent?" (opened by Mr. G. F. Shotter and Mr. A. W. Barham).

(2) "Special Tariff Prepayment Meters" (opened by Mr. E. Fawssett).

(3) "Is the Calibration of Watt-hour Meters with their Transformers Desirable?" (opened by Mr. A. J. Gibbons, speaking in favour of calibration, and Mr. Wilfred Holmes in opposition).

The meeting terminated at 10.15 p.m. with a vote of thanks, moved by the chairman, to those members who had introduced the subjects for discussion.

28TH MEETING OF THE METER AND INSTRUMENT SECTION, HELD JOINTLY WITH THE WIRELESS SECTION, 8TH APRIL, 1932.

Mr. F. C. Knowles, Chairman of the Section, took the chair at 7 p.m.

A paper by Mr. H. R. Harbottle, B.Sc.(Eng.), Associate Member, entitled "Some Acoustic and Telephone Measurements," was read and discussed.

The meeting terminated at 9.25 p.m. with a vote of thanks to the author, which was moved by the chairman and carried with acclamation.

29TH MEETING OF THE METER AND INSTRUMENT SECTION, 29TH APRIL, 1932.

Mr. F. C. Knowles, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meetings held on the 18th March and on the 8th April, 1932, were taken as read and were confirmed and signed.

The Chairman announced that the Committee had nominated the following to fill the vacancies which would occur on the Committee on the 1st October, 1932:—

Chairman: R. S. J. Spilsbury.

Ordinary Members of Committee: T. S. Andrew, O. Howarth, Prof. J. T. MacGregor-Morris, and Dr. E. H. Rayner, M.A.

Messrs. W. E. C. Alliss and H. Honey were appointed scrutineers of the ballot for the election of new members of the Committee.

Dr. C. V. Drysdale, O.B.E., Member, then delivered a Lecture entitled "Future Progress in Electrical Measuring Instruments."

A vote of thanks to the lecturer, proposed by Mr. R. S. J. Spilsbury and seconded by Mr. F. E. J. Ockenden, was carried with acclamation.

The meeting terminated at 9 p.m.

Informal Meetings.

143RD INFORMAL MEETING (11TH JANUARY, 1932).

Chairman: Mr. M. Whitgift.

Subject of Discussion: "The Relative Importance of Current and Installation Costs as affecting the Sale of Electricity." (introduced by Mr. H. T. Young).

Speakers: Messrs. F. Selley, J. Lesser, A. N. D. Kerr, W. Ritchie, General C. B. Legge, Messrs. J. R. Bedford, W. Jones, J. F. Shipley, Miss J. Whitgift, Messrs. C. F. Mounsdon, A. Morgan.

144TH INFORMAL MEETING (25TH JANUARY, 1932).

Chairman: Mr. H. M. Proud.

Subject of Discussion: "Engineering Conditions in Russia" (introduced by Mr. J. C. Wigham).

Speakers: Messrs. A. Morgan. R. Grigg, A. H. Olson, W. S. Percival, S. Flax, G. K. Johnson, D. B. Hoseason, P. J. Higgs, L. S. Crutch, A. N. D. Kerr.

145TH INFORMAL MEETING (15TH FEBRUARY, 1932).

Chairman: Mr. R. Grierson.

Subject of Discussion: "Electro-Medical Appliances in General" (introduced by Mr. G. G. Blake).

Speakers: Messrs. D. A. Stewart, J. F. Shipley, C. M. Davies, E. Megaw, Dr. B. J. Leggett, Messrs. W. Rennie, F. L. Veale, A. A. Linsell, M. Whitgift, A. Harmer, P. G. A. H. Voigt, R. Leach.

146TH INFORMAL MEETING (29TH FEBRUARY, 1932).

(JOINT MEETING WITH THE BRITISH SECTION OF THE SOCIÉTÉ DES INGENIEURS CIVILS DE FRANCE.)

Chairman : Mr. W. Bradshaw.

Subject of Discussion : "The Standardization of the Frequency of Electricity Supply in Paris" (introduced by Mr. P. Rieunier).

Speakers : Messrs. J. W. Beauchamp, W. E. Highfield, Roger T. Smith, J. F. Shipley, A. F. Harmer.

147TH INFORMAL MEETING (21ST MARCH, 1932).

Chairman : Mr. J. F. Shipley.

Subject of Discussion : "The Electrical Recording of Sound" (introduced by Mr. G. H. Nash, C.B.E.).

Speakers : Messrs. W. A. Ritchie, R. W. Hardisty, C. R. Keith, R. Mines, F. A. Cobb, S. Hill, J. R. Bedford, H. J. Neill, A. D. Blumlein, V. J. Terry, P. G. A. H. Voigt, G. F. Bedford, A. J. Gill.

148TH INFORMAL MEETING (11TH APRIL, 1932).

Chairman : Dr. A. Rosen.

Subject of Discussion : "The Modern Trend of Design of Broadcast Receivers" (introduced by Mr. C. F. Phillips).

Speakers : Mr. P. G. A. H. Voigt, Lieut.-Commdr. Sir P. W. Bowyer-Smyth, Bart., Dr. L. E. C. Hughes, Messrs. P. K. Turner, F. A. Cobb, G. C. Allingham, M.B.E., W. E. Bradshaw, A. G. McDonald, F. Jervis Smith, M. G. Scroggie, A. J. Gill, Lieut.-Col. H. P. T. Lefroy, D.S.O., Messrs. E. J. Wilby, A. Morgan, R. Mines.

Elections and Transfers of Members.

At the Annual General Meeting held on the 5th May, 1932, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Allcock, William Rayner.
Gibbard, Henry England.
Jackson, Ernest.
McPetrie, James Stuart, B.Sc.
O'Reilly, Eugene Leo, B.E., B.Sc.
Ratcliffe, John Ashworth.
Rhodes, George Leslie, M.A.
Ridge, Thomas William.
Riley, John Hesketh.
Simpson, Thomas George.
Smith, Percy Edward.
Walker, Joseph.
Wilkinson, Leslie Fielding.
Woods, Edmond William.

Associates.

Burdick, Stanley George.
Hird, Frederick.
Matthews, William.
Vickers, John.
Virr, Leonard Kirby.
Whibley, Joseph Herbert.

Graduates.

Armstrong, John Stewart.
Duckworth, Arthur William S.
Grayrigge, Fletcher.
Joslin, William Harris.
Kennedy, Geoffrey Farrer, B.A.
Markwick, Alfred Herbert D., B.Sc.
Noakes, Dorothy May (Miss), B.Sc.
Penney, Alfred Charles, B.Sc.
Stewart, David.
Toner, Harold Norman.
Vodden, Charles Edwin.
Whipple, George Allan, B.A.
Zaki, Said.

Students.

Alford, Ronald William C.
Balean, Henry Hamilton.
Ballou, Andres Bonfante.
Banfield, Bernard John.
Barrass, George Smith, B.Sc (Eng.).
Barrett, John Ernest.
Bousfield, Robert Hugh.
Brown, Archibald Leslie.
Bury, Ronald.
Butler, Hector.
Canto, Alfred Matthias.
Cooper, Reginald Amyas.
Cope, John Henry W.
Corbin, Clive Wilson.
Cosier, John Edward G.
Dobson, Frank John B.
Dent, Guy Alan.
Dubash, Mahiar Dhunjishaw.
Dumert, Victor.
Foster, Reginald Sydney.
Hooper, Stanley Leonard.
Harding, Robert Joseph.
Heywood, Geoffrey.
Jain, Jagdish Chandra.
Jennett, William Joseph.
Kenyon, Philip.
Kerrison, Frederick Leonard.
Kirkpatrick, Kenneth Sutton.
Kirkup, Ralph William.
Layzell, Albert Cyrus.
Linnell, Charles Edward.
Littlejohn, George William.
Misra, Lal Chand.
Neill, Stanley Francis M.
Olsen, Peter Louis.
Potts, Russell.
Preedy, George Martin.
Pyle, Bernard Charles.
Raven, Arthur.
Rogers, Basil James.
Sheikh, Kabir Ahmad.
Sheppard, Henry John.
Silverman, David.
Smith, Eric Stanley.
Sparke, George Douglas.
Stevenson, Geoffrey Lancaster.
Strafford, Frederick Richmond W.
Street, Walter George.
Swain, Edwin Charles.
Sykes, Allan.
Trenhaile, Clifford.
Vajifdar, Darab Hormusji.
Vardey, William Edward.
Wahid, Abdul.
Warner, Norman Edward.
Watkin, John Robert.
Whinfield, Frederick Raymond S.
Wilkins, Sydney Rutherford.
Wilkinson, William Raymond.
Williams, Emrys.
Wood, William Stanley.

TRANSFERS.

Associate Member to Member.

Bentley, John.
Campbell, Henry Arthur.
Elliott, Claud John.
Ramsey, Arthur George, M.B.E., B.Sc.(Eng.).
Spilsbury, Robert Samuel J., B.Sc.(Eng.).

Associate to Associate Member.

Jones, Walter Ernest.
Rowell, John Periam.
Royle, William Arden.
Wilson, James Haynes.
Woodcock, Herbert William.

Graduate to Associate Member.

Anderson, James Peter.
Boldy, Tigran David.
Cooper, Eric Raymond.
Evans, Evan John, M.Sc. (Eng,).
Farnes, Gilbert Henry, B.Sc.(Eng.).
Fraser, Herbert James.
Godden, Frederick William.
Gowdridge, Francis.
Hayes, Leslie William.
Isterling, Jasper.
Landale, Stenard Ernest A., Ph.D.
Mayer, Cornelius Graham.
Mead, Edward Michael K., B.A.
Newhouse, Kenneth Henry A.
Osment, Cyril George, B.Sc. (Eng.).
Peel, George Neville, B.Sc.
Rooney, James Louis, M.Eng.
Waters, George, B.Sc. (Eng.).

MODERN BOILER PLANT.

By JOHN BRUCE, Associate Member.

[*Paper first received* 11*th August, and in final form* 3*rd December*, 1931; *read before* THE INSTITUTION 10*th March, before the* NORTH-WESTERN CENTRE 26*th January, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 7*th March, before the* WESTERN CENTRE 14*th March, and before the* EAST MIDLAND SUB-CENTRE 22*nd March*, 1932.]

SUMMARY.

The subject matter of the paper is divided under the following headings:—

Introduction.
Thermal efficiency.
Operation costs.
Reliability.
Factors in design affecting reliability and operation.
Flue gas, dust and sulphurous fume extraction.
Arrangement of boiler plant.
Acknowledgments.
References.

Introduction.—In the Introduction a brief survey is made of the present position of boiler plant design in this country and America. The outstanding thermal performance of modern American generating stations is commented upon, and it is shown that these results are in no small measure the effect of American boiler plant development. The greatest difference in the trend of design between the two countries is in the wider adoption of higher operating steam pressures for American generating stations, the increase in individual boiler unit capacity, and the extended use of pulverized fuel firing, particularly on the unit system.

Thermal efficiency.—Under this heading present-day thermal results of British boiler plant are discussed, and examples are given of such results for both stoker-fired and pulverized-fuel-fired boiler plants.

Operation costs.—In this part of the paper the importance of repairs and maintenance costs is stressed. Examples are given of these costs for two large pulverized-fuel installations and one large stoker installation.

Reliability.—The reliability of modern boiler plant is discussed under this heading, and the reliability of a large pulverized-fuel-fired British plant is given in analytical tabulated form and also graphically, showing the hours of availability lost as a result of outage, and the cause of such outage. Three examples are given on a somewhat similar basis of the reliability of American plants. The various factors affecting reliability in general are discussed.

Factors in design affecting reliability and operation.—This section of the paper is subdivided under the following headings:—

(*a*) Water-heating and evaporative parts (boiler and economizer).
(*b*) Superheater.
(*c*) Combustion chamber.
(*d*) Combustion equipment.

Under (*a*) the author discusses the trend towards higher ratings and the results accruing from such practice. He suggests that the conventional present-day boiler form is unsuitable for development for high rates of heat transfer, and that such rates can only be effected by radiant heat, necessitating very radical changes in boiler unit form. He suggests, in general, that for the commonly accepted boiler-unit forms the average rate of evaporation per square foot of total water-heating surface at normal load should not exceed 5·5 lb. per hour. The need for further development of soot-blowing apparatus is discussed under this sub-heading.

Under (*b*) the trend in superheater design is discussed, and the vulnerability of the modern superheater location is emphasized. It is suggested that with the demand for still higher superheats, development in design is necessary to provide a superheater location where definite and separate control of superheat temperature can be effected. Superheater troubles within the experience of the author are given, and these include records of temperatures which superheater tube materials have to withstand in everyday practice.

Under (*c*) the author discusses and emphasizes the importance of combustion chamber design, and suggests that the boiler parts proper should be designed and arranged in dependent relation to the combustion chamber. The development of the water-cooled combustion chamber is briefly outlined, and the various advantages and limitations are discussed. The form of the combustion chamber and factors affecting reliability of refractory and water-wall construction are discussed.

Under (*d*) the author discusses the relative merits of stoker and pulverized-fuel combustion equipment, and suggests that pulverized-fuel firing has many advantages over stoker plant. These advantages are discussed, but the suggestion is qualified by the necessity for designers, constructors and operators being thoroughly conversant with the subject of pulverized-fuel plant design and operation.

This section is followed by a discussion of the relative merits of the unit and bin-and-feeder systems of pulverized-fuel plant, and the author suggests that the greater reliability and other advantages of a form of bin-and-feeder system cannot be ignored.

It is suggested that the adoption of boiler units of greater capacity for the modern large generating station has many advantages without sacrificing reliability or incurring greater costs, and a further suggestion is made and briefly discussed in favour of pulverized-fuel-fired units of not less than 500 000 lb. of steam per hour.

Air-heater equipment is discussed in this section of the paper, and the author criticizes and discusses modern design. He suggests simplicity in form and construction and greater attention to the laws governing the flow of air and gases. A brief survey of one phase of the author's experience in the application of high-temperature air to stoker practice is given and conclusions are reached. These latter were principally the necessity for cooling the grate surface to at least 350° F. and limiting the air temperature to this value. This section concludes with a survey of the author's experience with a large pulverized-fuel installation.

Flue gas, dust and sulphurous fume extraction.—The author has the honour to be a member of the Chimney Emissions Committee set up by The Electricity Commission, and also a member of the Technical Sub-Committee, and therefore he cannot freely discuss dust and sulphurous fume extraction in the present paper.

Arrangement of boiler plant.—In this final section of the paper the relative merits of the accepted forms of boiler-plant lay-out are considered.

INTRODUCTION.

It is intended to confine this paper to a survey of present-day practice in the design, construction and operation of the conventional types of boiler plant forming the steam generating equipment of the modern

electrical power station. An attempt is also made to show how certain factors, evolved from present-day experience, will influence the trend in design of steam generating units and the lay-out of boiler plants in the immediate future.

Though this survey deals principally with present-day British practice and the trend of development in this country, references and comparisons are made to representative contemporary design in the United States of America.

To prevent the paper assuming encyclopædic dimensions the subject is treated in general, but, where necessary, the matter is discussed in detail. The paper has been compiled from the author's own experience and a study of contemporary literature, principally reports of the proceedings of British and foreign technical institutions, coupled with information from private sources. Frequent reference is made to data published in the aforementioned reports, and it is felt that complication of the text will result if acknowledgment is made on every occasion. It is hoped, therefore, that wherever the author has omitted to make clear the title of the authority quoted the list of references appended to the paper will be accepted as due acknowledgment.

A study of present-day American conditions and an analysis of the statistical reports of that country leads one to the general conclusion that the best American generating stations have a better average thermal efficiency than those representative of best average British practice. A number of American generating stations are consistently producing a kilowatt-hour for a heat expenditure of under 14 000 B.Th.U. A further analysis indicates that this is due in a large measure to the advanced state of boiler plant development and the fact that a high standard of employee is used for boiler plant operation. Both these factors make possible the maintenance of high boiler-house thermal efficiencies over long periods.

Table 1 shows boiler-house efficiencies of representative American generating stations. The efficiency values are the average of the plant performance for periods of not less than one month and are not the result of short-period tests. The table has been compiled from data abstracted from recent N.E.L.A. reports and from private sources. The efficiencies are calculated on the gross calorific value of the coal as fired.

Table 1 must not be taken as showing a comparison between different combustion methods. The stations itemized have each a superlative overall thermal performance, and the difference in boiler-house efficiencies is accounted for by the method in which the thermal cycle has been balanced between boiler and turbine plant. The table merely sets forth the effect of recent boiler plant development on the maintenance of high boiler-house efficiency.

TABLE 1.

Boiler-House Efficiencies of Representative American Generating Stations.

Company	Station	Boiler-house efficiency (including banks)	Type of boiler	Combustion equipment
		per cent		
Cleveland Electric Illuminating Co.	Avon	87·3	B. & W. (Babcock & Wilcox) Twin Stirling	Central system, pulverized fuel
Detroit Edison Co.	Trenton Channel	87·0	B. & W. Stirling "W" type and Walsh Weidner "W" type	Central system, pulverized fuel
The Duquesne Light Co. ..	Colfax	87·2	B. & W. cross drum	Central system, pulverized fuel
Illinois Electric Power Co...	E. Peoria	83·8	Springfield	Central system, pulverized fuel
Philadelphia Electric Co. ..	Richmond	87·0	W. type	Stoker
Union Gas and Electric Co..	Columbia	87·0	B. & W. cross drum	Central system, pulverized fuel
State Line Generating Co. ..	State Line	84·4	B. & W. cross drum	Unit system, pulverized fuel
Super-Power Co., Illinois ..	Pekin	84·5	B. & W. cross drum	Unit system, pulverized fuel

The principal factors which make these plant performances possible are:—

- The close attention given to the design and construction, particularly in detail, of boiler-house equipment for long continuity and reliability of service.
- The good quality, and particularly the consistency, of the coal supply.
- The use of large boiler units.
- The facilities provided for ease of operation.
- The basis of contract guarantees relative to plant performance.

These factors will be more fully discussed later in the paper.

During the past two years American development has shown a marked increase in individual boiler unit capacities, and the present tendency is towards one boiler unit per turbine, with a spare to cover outages. Large boiler units capable of evaporating 1 million lb. of water per hour have been successfully designed, built and put into operation. This phase of development has been facilitated by the size of the distribution systems, coupled with the fact that, as a result of the rapid growth of connected load, new generating stations are designed much more frequently than is the case in this

country. The adoption and development of the water-cooled furnace for both stoker and pulverized-fuel combustion equipment has progressed to the extent that it is now standard practice, and the high rates of evaporation per square foot of total evaporative heating surface accredited to modern American boiler design is due to the use of large cooling surfaces in the combustion chamber, where high heat-transfer rates can be efficiently and economically utilized. In some cases as much as 65 per cent of the total heat liberated in the combustion chamber is absorbed by the water walls. The development of the water-cooled furnace has, further, proved to be a beneficial factor in the maintenance of long periods of operation. As will be shown later, boiler plant outages are mostly due to maintenance of furnace refractories, and the development of the furnace water wall has reduced this maintenance to a minimum.

Development in the use of higher steam pressures in America has followed two distinct tendencies:—

(*a*) Boiler plants designed for a working pressure between 500 to 650 lb. per sq. in. in combination with either reheat or non-reheat turbine units.

(*b*) Boiler plants designed for a working pressure between 1 200 and 1 400 lb. per sq. in. in combination with reheat turbine units.

Though the majority of America's newer generating stations are operating on the lower pressures, and the extent of development indicates a stabilization of design around these pressures, it is noteworthy that at the time of writing there are over 15 boiler units operating successfully and with no serious troubles in the neighbourhood of the high pressures. A study of American practice indicates that in considering the design of a new station the decision between the adoption of 600 lb. per sq. in. and 1 200 lb. per sq. in. operating steam pressures is governed by the cost of coal, the anticipated load factor over the life of the plant and the increased capital costs which are involved by the adoption of the higher pressures. The capital cost increases rapidly with increase in pressures above 600 lb. per sq. in., but the improvement in efficiency increases slowly. If good quality coal is obtainable at 4 dollars per ton of 2 000 lb. and the load factor is under 50 per cent, the increase in capital charges may more than offset the gain in heat efficiency resulting from the adoption of the higher pressures. Further, for the reasons already stated, the advantageous use of large units is facilitated, but the largest turbine yet considered for these higher pressures has a capacity of only 14 000 kW.

Development in the adoption of higher steam temperatures is limited, owing, as in this country, to the lack of suitable materials and the limited knowledge of the behaviour of available alloys at elevated temperatures. The present point at which design appears to be stabilized is in the neighbourhood of 800°–850° F., but valuable pioneer work on a commercial scale is being done by the Detroit Edison Co., who are putting a plant into commission to operate with a steam temperature of 1 000° F.

Development in the design of the evaporative components of the boiler unit has shown no radical changes from accepted standard practice, and apart from increases in size they still retain their conventional form. The steaming economizer has, however, been adopted in a number of new stations and has proved practicable and satisfactory.

The development of combustion equipment in America is considerably assisted by an advantageous factor which is non-existent in this country. The geological characteristics of the coal measures are such that combustion equipment can be developed for a particular coal, and the reserves are such that a station can be laid down to operate for the whole of its life on that coal. Consistency of coal quality has already been referred to. Further, most American coals are supplied to the generating station as lump or "run of mine," free from duff and smalls, and the subsequent crushing and handling is designed to deliver a uniformly graded product which, it is considered, is of special benefit to both stoker and pulverized-fuel equipment.

The development of the large boiler unit has assisted in the determination of the type of applicable combustion equipment. The chain-grate type of stoker becomes uneconomical from a first-cost point of view, and also meets structural difficulties compared with pulverized-fuel firing, when considered for boiler units having a greater evaporation than 200 000 lb. per hour. The serious rival to pulverized-fuel firing is the retort or cascade type of stoker, and it is considered by responsible American engineers that this type of equipment can be developed to form an efficient alternative for large boiler units.

The trend in development in pulverized-fuel equipment is towards the unit system. This is reflected in the returns for 1930, which show that the number of unit-system pulverized-fuel-fired stations under construction was three times that of stations designed for operation on the central system. The published data of the operating results of both systems show that equal performances can be obtained with either, but with capital charges slightly favouring the unit system.

Figs. 1 and 2 show cross-sections of typical modern American boiler units.

British practice in boiler plant development during the last few years, though not so ambitious as that in America or so productive of superlative thermal results, has, nevertheless, been worthy of note.

The most outstanding feature in boiler plant design in this country is the development of combustion equipment, particularly in relation to mechanical stokers.

The introduction of pulverized-fuel firing occurred at a time when there was a growing demand for an increase in boiler unit capacity and rating. The mechanical stoker equipment available at that time placed a definite limit on the development of boiler unit capacity, and for a period the adoption of pulverized-fuel firing met with considerable favour, since it gave unrestricted scope to the boiler designer. The impetus thus given to mechanical stoker design to meet this competition is reflected in the greatly improved performance of this type of equipment.

Two types of mechanical stoker are in use, namely

the travelling grate and the cascade or retort type. The former has reached a stage of development which permits its adoption for boiler units up to 250 000 to 300 000 lb. per hour. The first cost of the modern travelling-grate stoker has, however, increased in more

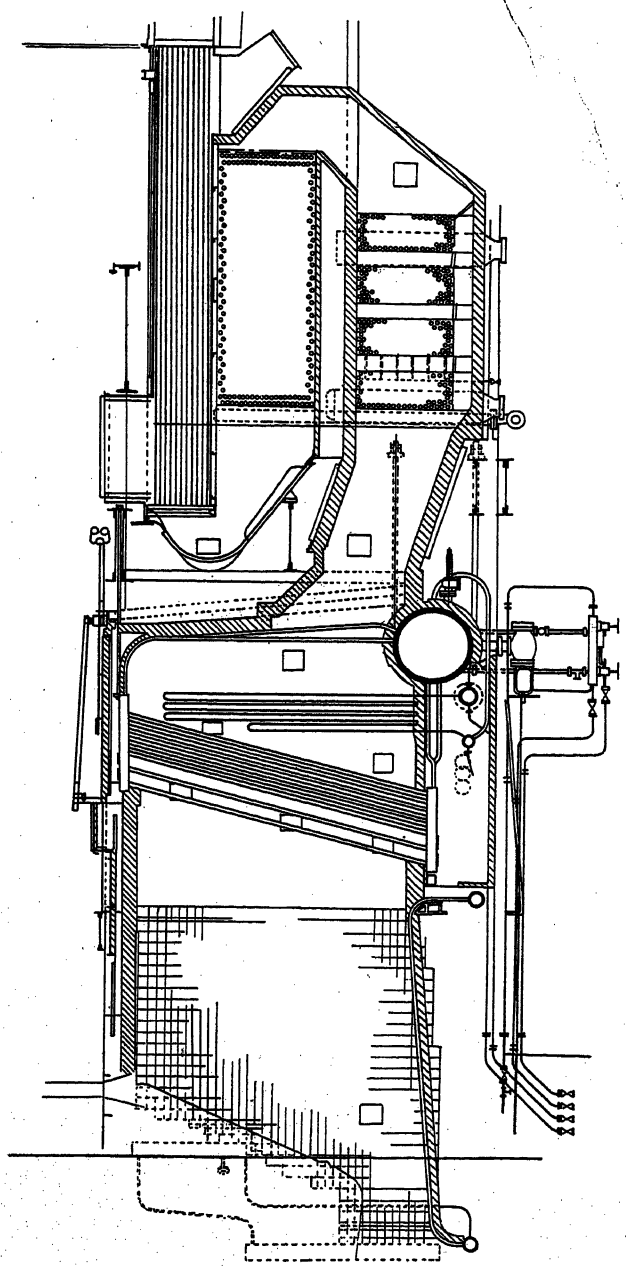


FIG. 1.—Cross-section of boiler unit (Edgar station, Edison Electric Illuminating Co., Boston).

than direct ratio to the increase in size. This increase in cost is the result of more than capacity increase. Stoker designers had an additional problem to solve by the rapid adoption of preheated air for combustion. Further, the demand for higher combustion efficiency necessitated greater attention to detail in construction, particularly in the design of the travelling grate surface, the distribution of air to the fire bed and the layout and arrangement of controls. Stokers of this modern type are in service and operating up to combustion rates of 70 to 80 lb. per sq. ft. of grate area. Many difficulties in the application of preheated air to travelling-grate stokers have been met, and the maximum air temperature that can be satisfactorily designed for, when burning the average steam-raising bituminous rough slack coals, is in the neighbourhood of 350° F. The question of preheated air temperature and its effect on combustion and on the behaviour of the stoker in practice is dealt with in greater detail at a later stage in the paper.

The development of the retort type of stoker in this country has not been on such an extensive scale, but its adoption for a number of the boiler plants in the stations of the London Power Co. is significant, and it is hoped that the discussion on this paper will include a record of the performance of these stokers. About twenty years ago this stoker found considerable favour with power-station engineers in Britain, but in service it was found that smoke prevention required critical control, and satisfactory performance was limited to certain coals. Since that period, however, the retort stoker has been improved out of all recognition, and if it can be developed in the future to operate successfully over a wide range of coals and with high preheated air temperatures, it will be the only rival to pulverized-fuel systems for the combustion equipment of the large boiler unit.

From a study of statistics relating to power stations or extensions in course of erection or in their first year of operation, it will be found that the majority of the boiler plants are arranged for stoker firing. The natural conclusion arrived at is that the adoption of pulverized-fuel systems has received a set-back.

Ten years ago the design and operation of pulverized-fuel equipment on a large scale was a little-known art in this country. Its introduction was heralded as the dawn of a new era. Manufacture of plant for this so-called new type of combustion equipment was undertaken by firms who knew little of their subject, and, when erected, the operation of this plant was in the hands of engineers who knew no more. These facts, coupled with the problem of dust emission from stacks, are the cause of the present-day position. In this country, representative pulverized-fuel-fired power stations of a capacity comparable with the pulverized-fuel-fired American stations included in Table 1 are few, and are represented by 150 000 kW of the boiler plant capacity at the Barking station of the County of London Electric Supply Co. (bin-and-feeder system), the Hams Hall station of the Birmingham Corporation Electricity Department (unit system) and the Brimsdown station of the North Metropolitan Electric Power Supply Co. (central system).

Development in the individual capacity of boiler units has been conservative. Ten years ago the layout design of combined boiler and turbine plant usually allowed for four boiler units per turbine unit, three boiler units being capable of steaming the normal load with one unit spare. To-day the same arrangement is the generally accepted practice. Turbine units have increased in capacity by about three times, and the

general increase in capacity of boiler units has been in similar proportion, thus retaining three boiler units to operate the turbine unit, with one boiler as spare. The present-day position, bearing in mind the fact that pulverized-fuel firing is temporarily out of favour and

necessity for research and experimental work on the design of this boiler plant component. It is the author's opinion that, having decided the type of combustion equipment to be employed, the combustion chamber design should be first determined and the evaporative

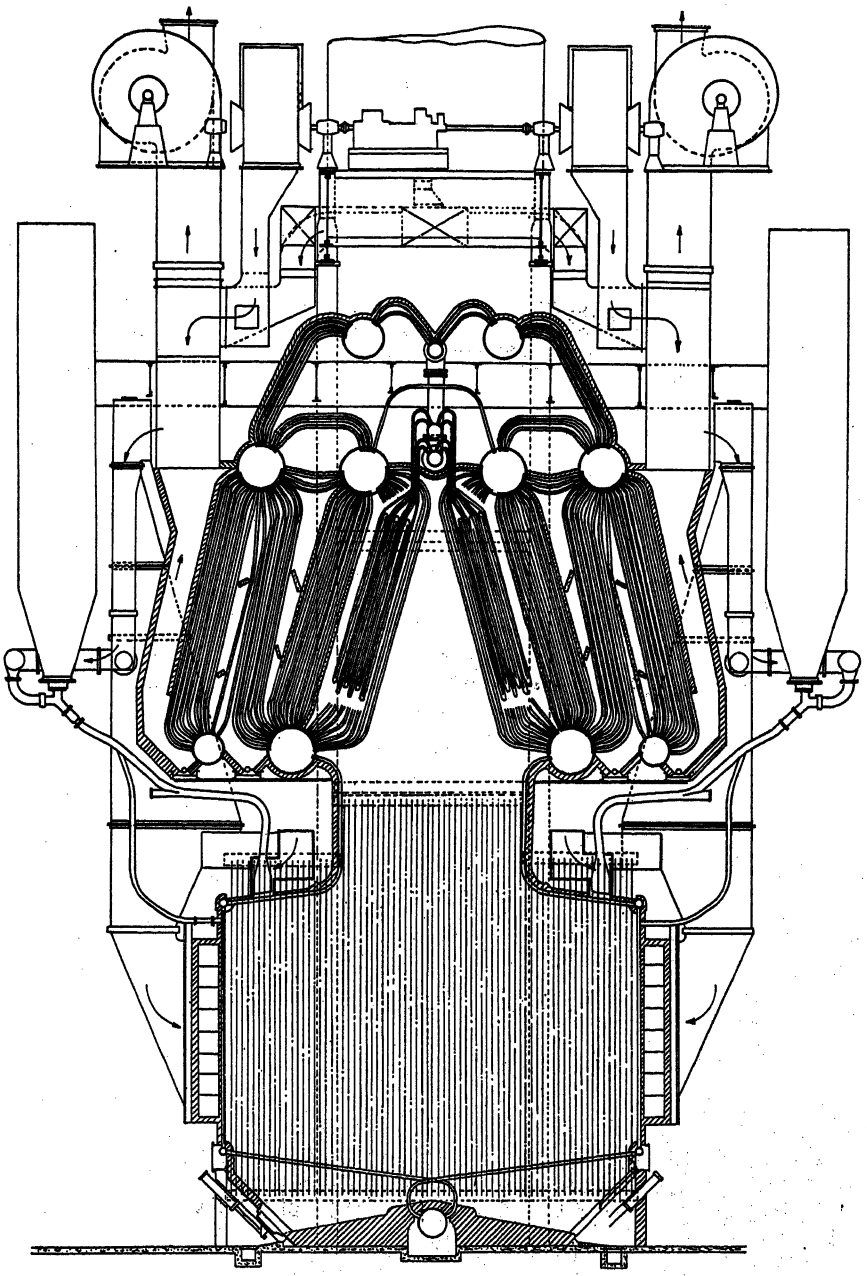


FIG. 2.—Cross-section of 1 000 000-lb.-per-hour boiler unit (East River station, New York Edison Co.).

that retort stoker development is not yet of an extensive character, indicates that the constructional problems of large travelling-grate stoker design will limit the capacity of boiler units in the immediate future to a maximum of 300 000 lb. per hour.

Combustion equipment development has shown the need for larger combustion chamber volumes and the components considered and arranged in dependent relation to this design.

Increase in combustion efficiency and the utilization of higher preheated air temperatures brought fresh problems to the combustion chamber designer. Walls of solid refractory were standard practice. Experience during the development of pulverized-fuel burner equip-

ment, from the early long-flame burner to the short-flame turbulent burner, showed the necessity for definite limits to the rates of heat release per unit volume of combustion chamber. Similarly, the same necessity was indicated during the development of stoker plant. Rapid deterioration of refractory was a problem to which considerable research was devoted. The result was the production of higher-grade material and the introduction of the air-cooled wall. Further development resulted in the introduction of water-cooling and the elimination of refractory, and the position to-day is that, with certain arrangements of pulverized-fuel firing adapted to a boiler unit of particular design and utilizing high preheated air temperature, the refractory can be entirely eliminated. On the other hand, where the design necessitates the partial use of refractory material it is possible to water-cool the whole of the combustion chamber, including the arches, by means of wall water tubes, and where required these can be encased in shaped refractory blocks.

Increase in boiler plant operating steam pressures is partly the result of the development in turbine design. The adoption of very high pressures for commercial purposes has been limited to one or two installations, notably the boiler plant of Imperial Chemical Industries at Billingham and the extensions to the power station plant of the Bradford Corporation Electricity Department.

Temporary stabilization of design is at present centred around 650 lb. per sq. in. (gauge).

Development in the application of higher steam temperature is limited, for reasons already stated, to a maximum of 850° F.

THERMAL EFFICIENCY.

The criterion of boiler plant performance is the overall cost of steam production, and the principal factors governing this are capital and operation costs, reliability, and the maintenance of high thermal efficiency. The cost of steam production is the overall cost of generating and delivering steam at the turbine stop-valves, and is made up of capital charges, operating costs of boiler plant and coal- and ash-handling plant, repairs and maintenance costs, including costs of renewal material and supervision charges.

The definition of overall thermal efficiency cannot be so simply set out, and from a consideration of the published thermal figures for various boiler plants it would appear that there is a considerable amount of confusion as to the meaning of this term. The thermal efficiency of an individual boiler is defined by the Institution of Civil Engineers' code. It will be generally agreed that the overall efficiency should be debited with all banking and lighting-up losses, and, it can be argued, it should also be debited with all range heat and water losses incurred between the boiler stop-valves and the turbine stop-valves and from the final bled steam feed-water heater to the economizer or boiler drum check valves. This leaves all leakage heat and water losses from the turbine and feed-water heater train to be debited against the turbine. The value of these losses is negligible compared with the main range losses, and it is suggested that the total of all these losses, usually referred to as radiation and make-up water losses, should be debited against the boiler plant, unless they can be readily measured and allocated. The whole question resolves itself into a decision as to where the boiler plant begins and ends, and from this argument it will be seen that the author suggests:—from the last bled steam feed-water heater, round the boiler cycle, and back to the turbine stop-valve. It is understood, of course, that all losses incurred as a result of steam soot-blower operation and blowing-down of boilers should be debited against the boiler plant.

At the other end of the cycle there are discrepancies in the methods of calculating the coal weight to be used in efficiency formulæ. For individual boiler tests it is correct to use the coal weight as supplied to the unit on test. For overall purposes, however, there are certain factors to be considered. The whole of the coal-handling plant is part of the steam generating equipment, and losses incurred between either rail-borne or sea-borne deliveries and the boiler plant bunkers should be debited against the efficiency. For example, windage losses on an exposed plant handling small, dry coal can be considerable. Summing up, at this stage it is seen that overall boiler plant efficiency would be

$$\eta = \frac{H \times W}{C} \times 100$$

where

η = overall efficiency, per cent.
H = total heat, B.Th.U. per lb., in steam at turbine stop-valve, minus heat in feed water, B.Th.U. per lb. at final h.p. bled-steam feed-water heater.
W = weight of steam in lb. supplied to main and house turbines divided by the total invoiced coal weight in lb., corrected for coal in stock.
C = calorific value of coal as received, B.Th.U. per lb. gross.

The author considers that the boiler plant overall efficiency should be further debited with its share of station auxiliary power, and should include all coal-handling and ash-disposal plant. Where electrically-driven auxiliaries are employed and the consumption of each section of the station is metered, the allocation is simple, but if this is not the case the allocation can be approximated if each item of equipment is provided with ammeters. Where steam-driven auxiliaries are employed the case is not so simple, but it is not very complicated.

Steam-driven boiler feed pumps, if considered as a boiler plant auxiliary, are correctly taken care of by the foregoing formula. Steam-driven turbine auxiliaries would, owing to the expense of individual metering, be credited to the boiler plant and debited against the turbine by calculation.

In the following remarks setting out the thermal performances of representative British power station boiler plants no attempt is made to draw comparisons. In fact, it will be obvious to most that it is impossible to consider any aspect of performance between one plant and another on a comparable basis.

Throughout this paper reference is made to the per-

Particulars of unit:—

Heating surface of boiler	16 510 sq. ft.
Heating surface of superheater	4 300 ,,
Heating surface of economizer	16 000 ,,
Heating surface of air heater	19 920 ,,
Heating surface of water walls	1 320 ,,
Heating surface of water screen	470 ,,
Number of burners	10
Combustion chamber volume	11 450 cub. ft.

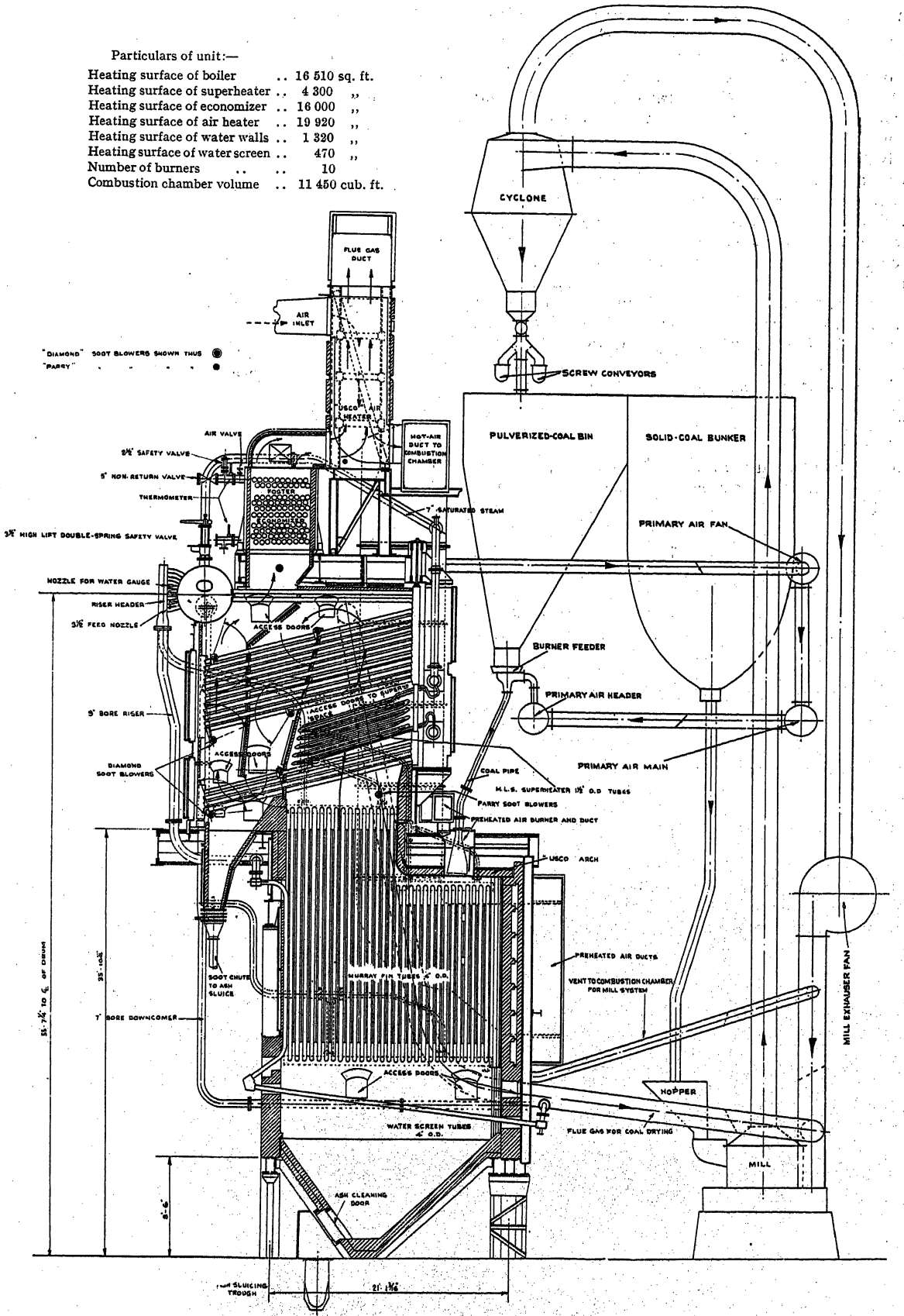


FIG. 3.—General arrangement (side sectional elevation) of boiler unit in large pulverized-fuel-fired British power station.

NOTE:—The coal-preparation plant is shown diagrammatically

formance of a large representative British pulverized-fuel-fired boiler plant constructed in 1927 and put into service in that and the ensuing year. The plant consists of 10 boiler units, each having a normal rating of 135 000 lb. per hour at 375 lb. per sq. in. (gauge) steam pressure and 725° F. total steam temperature, with feed water supplied at 260° F. at the economizer inlet. The boiler unit assembly comprises gilled-tube economizers and plate-type air heaters. The coal-preparation plant and combustion equipment is a modified bin-and-feeder system. Each boiler unit has its own coal-preparation plant, but a system of screw conveyors from the cyclone outlets interconnects the complete installation. The burner equipment consists of rotary feeder gear and ten fishtail straight-shot burners on each boiler unit. Each combustion chamber is water-cooled by fin tubes on three sides, which, together with the water-cooled tubular ash screen and the generating tubes of the boiler unit proper, give a cold fraction of five-sixths.

Fig. 3 shows a cross-section of a boiler unit of this installation.

Thermal performance in the early days of the operation of this plant is represented by the data set out in Table 2.

TABLE 2.

Test on No. 15 Boiler Unit.

Date test started	2.55 p.m. May 13, 1929
Date test finished	7.11 p.m., May 17, 1929
Duration of test	100 hours 16 minutes
Load on boiler unit	normal, 135 000 lb./hour

Water.

Total of 1-minute readings of Kent test meter	13 692 583 lb.
Total of 1-minute readings of Kent test meter (corrected for temperature)	13 725 445 lb.
Total of 1-minute readings of Kent test meter (corrected for meter error)	13 657 158 lb.
Average actual evaporation per hour	136 231 lb.
Average temperature entering economizer	250° F.
Average temperature leaving economizer	300° F.
Actual evaporation per lb. of coal	8·394 lb.
Equivalent evaporation per lb. of coal from and at 212° F.	11·98 lb.
Equivalent evaporation per lb. of coal from and at 212° F. per 10 000 B.Th.U. in coal	10·73 lb.

Steam.

Steam pressure in boiler drum	398 lb./sq. in. (gauge)
Steam pressure at superheater outlet	390 lb./sq. in. (gauge)
Steam temperature at superheater outlet	724° F.
Total heat in steam	1 381 B.Th.U./lb.

Steam (continued).

Total heat in feed water above 32° F.	218 B.Th.U./lb.
Total heat added in boiler, economizer and superheater	1 163 B.Th.U./lb.
Total heat added per lb. of coal	9 763 B.Th.U.

Coal.

Quality	Northumberland rough slacks
Total coal weighed entering mill	1 627 008 lb.
Average coal weighed entering mill per hour	16 229 lb.
Pyrites extracted from mill (total)	7 351 lb.

Average Analysis of 24-hour Samples determined by Independent Analyst.

	As fired, per cent	As dried, per cent
Moisture	8·26	nil
Carbon	59·84	65·23
Hydrogen	4·27	4·65
Sulphur	1·87	2·04
Nitrogen	1·15	1·25
Oxygen, etc.	8·97	9·78
Ash	15·64	17·05
Calorific value, B.Th.U./lb. (gross)	11 136	12 137
Calorific value, B.Th.U./lb. (net)	10 624	

Gas.

Average temperature leaving boiler	591° F.
Average temperature leaving economizer	395° F.
Average temperature leaving air heater	259° F.
Average CO_2 content at boiler exit	14·9 per cent
Average CO_2 content at economizer exit	13·9 per cent
Average CO_2 content at air heater exit	13·3 per cent
Average O_2 content at air heater exit	5·6 per cent
Average N_2 content at air heater exit	81·1 per cent

Air.

Average temperature entering air heater	108° F.
Average temperature leaving air heater	303° F.

Gas and Air Pressures.

Gas pressure in combustion chamber	− 0·14 in. of water gauge
Gas pressure at boiler outlet	− 0·65 in. of water gauge
Gas pressure at economizer outlet	− 1·10 in. of water gauge
Gas pressure at air heater outlet	− 3·10 in. of water gauge
Air pressure in forced-draft ducts	+ 0·8 in. of water gauge
Air pressure in secondary air ducts	+ 0·5 in. of water gauge
Air pressure in primary air ducts	+ 13·5 in. of water gauge

Heat Balance.

	B.Th.U.	Per cent
Heat added in combined unit ..	9 763	87·67
Heat lost in dry flue gases	405	3·64
Heat lost to moisture formed from H_2	422	3·79
Heat lost to moisture in coal ..	90	0·81
Heat lost to combustible in ash ..	147	1·32
Heat lost to radiation and unaccounted for	309	2·77
	11 136	100·00

Efficiency of unit on gross calorific value as fired .. .. .. 87·67 per cent
Efficiency of unit on net calorific value as fired .. .. .. 91·95 per cent
Heat release per cubic foot of combustion chamber .. 15 575 B.Th.U./hour

Power Consumption of Auxiliaries.

(1) *Boiler Unit.*	kW	Total kWh for test period
Forced-draught fan	22·41	2 244·9
Induced-draught fan, A ..	41·58	4 165·0
Induced-draught fan, B ..	41·60	4 166·6
Primary air fan	30·89	3 094·4
Burner feeder motor ..	1·73	173·0
Total	138·21	13 843·9
(2) *Coal-Preparation Plant.*		
Mill	161·30	8 272·80
Exhauster	94·00	4 780·70
Mill feeders and rotary air lock	0·73	37·35
Total	256·03	13 090·85

Coal-preparation plant running hours, 51 hours 5 minutes
Power consumption per ton of coal milled 18 kWh
Gas temperatures in mill system (coal drying in mill) .. ..
Average temperature of gas bled from boiler 698° F.
Average temperature of gas and air at mill inlet .. .. 280° F.
Average temperature of gas and air at mill outlet .. .. 143° F.

A year later, test data, over a period of approximately 100 hours, were again tabulated for the same boiler unit, and the results obtained are set out in Table 3.

TABLE 3.

Test on No. 15 Boiler Unit.

Date test started .. .. February 25, 1930
Date test finished .. .. March 1, 1930
Duration of test .. .. 98 hours, 15 minutes
Load on boiler unit .. .. normal, 135 000 lb./hour

Coal.

Quality .. Good quality slack, soft and friable
Total coal measured .. .. 1 286 987 lb.
Pyrites extracted .. .. .. 705 lb.
Actual coal consumed .. .. 1 286 282 lb.
Average coal consumed per hour .. 13 092 lb.

Analysis:—	As fired, per cent	As dried, per cent
Moisture (total)	3·33	nil
Volatile matter	25·03	25·89
Fixed carbon	58·18	60·19
Ash	13·46	13·92
Total	100·00	100·00
	Per cent	
Moisture (total)	3·33	
Carbon	69·87	
Hydrogen	4·43	
Sulphur	2·66	
Oxygen, etc.	6·25	
Ash	13·46	
Total	100·00	
Calorific value, B.Th.U./lb. (gross)	12 930·	13 370
Calorific value, B.Th.U./lb. (net)	12 474	—

Water.

Average evaporation per hour .. .. 134 600 lb.
(Temperature and meter corrections applied)
Average temperature of water entering economizer .. .. 264° F.
Actual evaporation per lb. of coal consumed 10·28 lb.

Steam.

Average boiler pressure .. 373 lb./sq. in. (gauge)
Average steam temperature at superheater outlet .. 711° F.
Total heat in steam at superheater outlet .. .. 1 370 B.Th.U./lb.
Total heat added in boiler, superheater and economizer 1 138 B.Th.U./lb.

Air and Gases.

Average temperature of air entering air heater .. .. .. 110° F.
Average temperature of gases leaving air heater .. .. .. 260° F.
Average CO_2 content of gases leaving air heater .. .. 13·5 per cent
Average O_2 content of gases leaving air heater .. .. 5·2 per cent
Average CO content of gases leaving air heater .. .. nil
Average N_2 content of gases leaving air heater .. .. 81·3 per cent

Heat balance.	B.Th.U.	Per cent
Heat added in combined unit	11 698	90·47
Heat lost in dry flue gases ..	472	3·65
Heat lost in moisture formed from H_2	437	3·38
Heat lost in moisture in coal	36	0·28
Heat lost in combustible in ash	29	0·22
Heat lost in radiation and unaccounted for	258	2·00
Total	12 930	100·00

Heat Balance.

Efficiency of unit on gross calorific value as fired ..	90·47 per cent
Efficiency of unit on net calorific value as fired ..	93·75 per cent.
Heat release per cubic foot of combustion chamber ..	14 750 B.Th.U./hour

Power Consumption of Auxiliaries.

(1) *Boiler Unit.*

	kW	kWh
Forced-draught fan	37·5	3 684·4
Induced-draught fan, A ..	33·5	3 289·2
Induced-draught fan, B ..	33·7	3 312·8
Primary air fan	40·7	4 000·0
Burner feeder motor ..	1·9	176·0
Total	147·3	14 462·4

(2) *Coal-Preparation Plant.*

Mill	114·3	3 691·2
Exhauster	100·0	3 233·8
Rotary air lock and mill feeders	1·1	34·6
Total	215·4	6 959·6

Coal-preparation plant running hours	32 hours 15 minutes
Power consumption per ton of coal milled	12·1 kWh

The operating period during which the foregoing data were obtained has been referred to as a test, but it was not a test in the usually accepted meaning of the word. The unit was operated by the ordinary shift firemen throughout, and beyond the fact that no fluctuations of load were accepted on this unit operation was of the ordinary routine nature. The measurements for the tabulation of results were, of course, made with test instruments and special observers.

Thermal performance figures produced under "test conditions" are not always a criterion of what the plant performance will be over long periods of operation. In fact, no thermal figures are of much value for commercial purposes unless they represent a period sufficiently long to show the effect of operating conditions, maintenance, changes in fuel quality, the general wear and tear of service, and the varying ability of the available class of operating labour. The figures set out in Table 4 are therefore of value, since they record the principal operating statistics of the pulverized-fuel boiler plant referred to for the year 1930.

The boiler plant referred to is only one section of the complete steam-generating plant, and since the steam ranges, receivers, etc., are common to the whole plant separate measurement of the make-up losses cannot be made for each boiler house. Similarly, separate measurement is not made of auxiliary power, but from collected data these values can be approximated by estimation. Allocating the proportion of these losses against the above efficiency figure, the overall boiler-house efficiency for the year is in the close neighbourhood of 85 per cent.

It is hoped that the discussion on this paper will be productive of further thermal performance data relative to other pulverized-fuel installations in this country, and covering long periods of operation.

One of the most representative stoker-fired installations in this country is the boiler plant of the Deptford West power station of the London Power Co. Ltd. A full description of this plant is contained in a paper read before the Institution of Civil Engineers, 14th April, 1931, and the author has taken the liberty of quoting from that paper figures relative to the Deptford West boiler plant.

TABLE 4.

Operation Statistics of Pulverized-fuel-fired Boiler House referred to, for year 1930.

Total coal consumed for all purposes	292 088 tons
Total water evaporated ..	5 300 000 000 lb.
Average steam pressure at boiler	380 lb./sq. in. (gauge)
Average steam temperature at superheaters	715° F.
Average feed-water temperature at h.p. bled-steam heaters	260° F.
Average calorific value of coal as fired	10 700 B.Th.U./lb. (gross)
Boiler plant thermal efficiency	88·8 per cent

In Appendix VI of that paper are given typical thermal test-results of boiler units equipped with travelling-grate or retort-type stokers. The data refer to units having normal evaporation rates of from 75 000 to 100 000 lb. per hour at a steam pressure of 375 lb. per sq. in. (gauge) and a total steam temperature of from 750° F. to 780° F.

The principal results of the series of tests referred to have been extracted and are set out in this paper in Table 5.

Appendix VIII of the same paper tabulates the station operating results for 1930 and also for the last quarter of that year, and the items referring to the boiler plant operation are set out here in Table 6.

The generating stations of the Lancashire Electric Power Co. have, in recent years, received a considerable amount of prominence as a result of their salient design features, low capital cost per kW installed, and the outstanding superiority of the thermal results obtained. The boiler plant of the Kearsley station of that company is representative of simple, straightforward British practice. The boiler units are equipped with travelling-grate stokers of very generous design. Similar generosity is reflected in the allocation of heating surfaces, with the result that under normal load conditions each component of the boiler plant is operating well within its capabilities.

The operation results of the boiler plant of the Kearsley station for the year 1930 are set out in Table 7.

The foregoing examples of thermal performance are sufficient to show the results commercially attainable over long periods with our present-day designs, and the

TABLE 5.

*Boiler Test Results.**

Type of boiler	Small sectional cross-tube marine type		Small vertical bent-tube type		Large sectional cross-tube marine type	
Boiler rating	Normal evaporation rating	Maximum continuous rating	Normal evaporation rating	Maximum continuous rating	Normal evaporation rating	Maximum continuous rating
Class of coal	Scotch washed peas	Scotch washed peas	Scotch washed peas	Scotch washed peas and singles	Washed smalls	Washed smalls
Gross calorific value of coal as fired, B.Th.U./lb.	11 288	11 249	11 558	10 941	11 278	11 342
Lb. of coal burnt per sq. ft. of grate per hour	23·68	30·60	36·20†	51·07†	21·40	28·70
Hot-air temperature to grate, ° F.	248	261	224	265	218	233
Heat energy release in combustion chamber, B.Th.U./cub.ft./hour	28 437	36 732	18 535	24 700	23 938	32 311
Heat absorbed by boiler plant (gross boiler efficiency, per cent)	87·51	86·27	86·43	85·86	87·73	85·97
Heat lost in dry flue gases, per cent	3·75	4·01	4·13	5·84	3·10	3·48
Heat lost in evaporating moisture in coal, per cent	1·28	1·36	1·30	1·74	1·52	1·54
Heat lost in evaporating moisture due to H_2, per cent	3·71	3·70	3·61	3·84	3·67	3·78
Loss due to combustible matter in ash, per cent	0·62	0·86	0·42	0·31	0·56	1·13
Radiation and losses unaccounted for, per cent	3·13	3·80	4·11	2·41	3·42	4·10
Total	100·00	100·00	100·00	100·00	100·00	100·00
Equivalent power absorbed by auxiliaries	1·35	1·49	0·89	1·10	1·61	2·03
Net boiler efficiency, per cent	86·16	84·78	85·54	84·76	86·12	83·94

figures are of further interest since the fuels used are drawn from separate coalfields. To repeat what is possibly a platitude, it is apparent that in boiler plant design we have reached the upper limit of attainable efficiency if we except the further small gain available if and when the utilization of high preheated air temperatures becomes commercially practicable.

OPERATION COSTS.

Thermal-efficiency statistics can only have an academic interest unless they are accompanied by an analytical statement of the cost involved. This cost, neglecting standing charges, is composed of two principal items, viz. operation costs and repairs and maintenance costs. Of these two, the latter is the more important and is liable to assume uneconomic proportions.

In Table 8 is given an analysis of the repairs and maintenance costs (labour, supervision and material) of

* Extracted from "The Deptford West Power Station of The London Power Co. Ltd.," paper by C. S. Berry, H. P. Gaze and C. E. H. Verity, read before the Institution of Civil Engineers 14th April, 1931.

† On net area of retort stoker, excluding ashpit.

TABLE 6.

Operation Returns.‡

	4th Quarter 1930	Year 1930
Total coal burnt, tons	39 752	144 901
Total coke burnt, tons	8 258	19 357
Fuel used for banking and lighting-up, tons	783	2 957
Average gross calorific value at boilers, B.Th.U./lb.	11 270	11 232
Average steam pressure at boilers, lb./sq. in (gauge)	380	378
Average steam temperature at boilers, ° F.	775	769
Average water temperature at economizer inlet, ° F.	236	234
Boiler efficiency, per cent	82·53	82·37
Net running boiler efficiency, less banking, per cent	83·90	83·87

‡ Extracted from "The Deptford West Power Station of The London Power Co. Ltd.," *loc. cit.*

the pulverized-fuel plant previously referred to, in relation to the coal consumed for the four months ending 31st December, 1930. As previously stated, this plant was one of the earliest pulverized-fuel installations on a large scale to go into commission in this country. The plant has been in service continuously for three years, and much has been learnt in that time. The mechanical performance of the coal-preparation plant lent itself to considerable improvement, and the cost of this improvement explains—and is reflected in—the high costs itemized against mills, exhausters, burners, fans, etc. It should be explained that this latter item includes repairs and maintenance of the boiler-unit main fans. The induced-draught fans, of which there are two per boiler, are installed before the grit arrestors, and, in consequence, repairs to the fan runners and casings form an appreciable item. As a matter of interest, the life of these fan runners is consistently between 6 000 and 7 000 hours.

Deducting the cost of repairs and renewals to the induced-draught fans, the maintenance costs of the coal-preparation plant alone are 12·48d. per ton of coal.

Table 9 gives repairs and maintenance costs of the coal-preparation plant obtained in the early part of the present year and shows the results of the improved performance.

The boiler plant of the Hams Hall generating station of the City of Birmingham Electric Supply Department is typical of recent design employing pulverized-fuel firing on the unit system, and the repairs and maintenance costs of this plant are given in Table 10.

Further figures relating to coal-preparation plant charges in connection with pulverized-fuel equipment will be discussed later.

TABLE 7.

Boiler House Statistics, for the Year ended December 31, 1930, of the Lancashire Electric Power Co., Kearsley Power Station.

Total weight of coal burnt	67 907 tons
Class and quality	Lancashire washed slack
Analysis (on dry basis):—	Per cent
Volatile matter	33·34
Fixed carbon	58·29
Ash	8·37
Total	100·00
Moisture	10·32 per cent
Calorific value as fired (gross)	12 160 B.Th.U./lb.
Combustible in ashes	5·59 per cent
Steam pressure (boiler drum)	316 lb./sq. in. (gauge)
Steam temperature (boiler stop-valve)	697° F.
Feed-water temperature entering economizers	195° F.
Flue-gas temperature leaving air heater	234° F.
Total weight of water evaporated	1 294 960 000 lb.
Water evaporated per lb. of coal	8·513 lb.
Boiler-house efficiency	84·10 per cent

TABLE 8.

Analysis of Pulverized-Fuel Boiler Plant, Repairs and Maintenance Costs, 1930.

Coal consumed	105 510 tons
	Pence per ton of coal
Boiler repairs	3·12
Furnace brickwork repairs	1·64
Mills, exhauster, etc., repairs	9·30
Burners, fans, etc., repairs	4·93
Screw conveyors	0·30
Ash removal plant	0·30
Total	19·59d.

TABLE 9.

Coal consumed	124 426 tons
	Pence per ton of coal
Mills, exhausters, cyclones, etc.	4·160*
Burners, feeders, ducts, coal-preparation fans, etc.	1·025
Screw conveyors	0·620†
Total	5·805d.

TABLE 10.

Boiler-House Statistics of the Hams Hall Power Station of the City of Birmingham Electric Supply Department.

	Cost per ton of fuel burnt pence
Boilers and air heaters.	
Labour and material maintenance, including boiler and air heater cleaning, preparing for survey and incidental expenses	2·53
Fans (forced- and induced-draught), ducting, etc.	
Labour and material maintenance	0·24
Furnace brickwork.	
Still under maintenance	—
Coal-preparation plant.	
Labour maintenance	0·485
Material	1·100
Operating wages, oil and grease	1·960
Total coal-preparation plant charges	3·545d.

Operation costs for large stoker-fired boiler units are fairly well known owing to the longer period of operation and much wider adoption of this type of plant. The figures in Table 11 will, however, be of interest since they represent the boiler-house costs over a long period

* Includes renewal of bull-rings and rollers, which are still in useful life.
† Includes cost of modifications, lagging and encasing with special blocks to two conveyors.

of one of the largest stoker-fired power station boiler plants in this country.

TABLE 11.

Maintenance Costs per Ton of Coal burnt for Power Station Boiler Plant equipped with Travelling-Grate Stokers.

	Pence
Boilers, economizers and air heaters ..	5·33
Induced- and forced-draught fans, ducting, etc.	0·01
Stoker repairs	5·45
Furnace brickwork	5·53
Total	16·32d.

Coal consumed during period covered by above costs	622 331 tons
Overall thermal efficiency, based on gross calorific value of coal as weighed, during period covered by above costs	79·41 per cent

RELIABILITY.

Reliability of existing designs of boiler plant is a subject seldom discussed publicly and in detail. It is a factor in boiler-house practice equally important as, if not more important than, thermal efficiency. The reliability of the large modern turbo-alternator and its auxiliaries has reached a degree far in advance of that inherent to the modern boiler unit. Investigation as to the reason for this points to the fact that one factor is lack of attention to detail in design and construction, coupled, in many instances, unfortunately, with an attempt to design and build a plant down to a price rather than up to a definite specification.

Some years ago, before our knowledge of boiler-water treatment for high-pressure conditions was as extensive as it is to-day, it was customary to limit the steaming periods of boiler units to enable examinations to be made of the internal surfaces. To-day that necessity does not arise. Where make-up water is a carefully prepared distillate, condenser leakage kept at a minimum, de-aeration properly effected, and the boiler-water conditioning for alkalinity and embrittlement inhibition competently supervised it should only be necessary to open a boiler unit for internal examination once a year, that is, when laid out of service for annual survey and overhaul.

The various components which together form the modern boiler unit are simple pieces of engineering apparatus, and individually are as reliable as turbo-alternator plant. The modern demand for high ratings per square foot of heating surface, high rates of heat liberation per square foot of grate area or per cubic foot of combustion chamber volume, resulting in excessive fan-power values and high-velocity gases, are further factors adversely affecting the reliability of modern boiler plant to a considerable extent.

If a plant is to be reliable in service the first necessity is generosity in design and a curbing of the desire for excessive ratings. Generosity in design does not necessarily mean an increase in first cost for a given capacity. One of the most reliable—and, at the same time, most efficient—power-station boiler plants in this country has heat liberation and heat transfer ratings less than half of what is considered "modern" practice, but nevertheless the plant referred to was built for a cost per kilowatt considerably less than many other stations with less pretentious operating records.

The second necessity is attention to detail—no matter how trivial the detail may appear on paper—and coupled with this is the necessity for simplicity in lay-out and of operating control.

In Table 12 is given a detailed analysis of the operation of the pulverized-fuel-fired boiler plant previously referred to, for the year 1930. This table gives the actual steaming hours of each unit and also the number of hours lost as a result of necessary repairs, which have been itemized for easy reference.

It will be noted that the majority of the hours lost are the result of furnace brickwork troubles and superheater defects. "Birdnesting" in the first bank of generating tubes was the cause of further lost hours on three units, particularly in the case of number 15. All these troubles will be discussed in detail later in the paper.

The number of hours lost as shown in the table is not, however, a full indication of the extent of boiler outage. For example, a compulsory outage period of 200 hours is not nearly so detrimental to reliability as four 50-hour outage periods occurring at short intervals of service. The data set out in Table 12 have, therefore, been further analysed and are set out in graphical form in Fig. 4. The reference letters over each outage period refer to the same letters against the itemized reasons for outage shown in Table 12.

It should be noted that on no occasion was the pulverized-fuel preparation plant or burner equipment the cause of any compulsory boiler outage.

The length of the periods shown for annual survey and overhaul in Fig. 4 are no indication of the amount of work involved. This work is done, if possible, without incurring overtime, and as there was ample plant to cover the system load none of the surveys was hurried.

The information given in Table 12 and Fig. 4 is all that the author has been able to obtain of this nature for boiler plants in this country. Since these figures only refer to one plant they cannot be said to be representative of the whole of present-day British practice.

It was stated earlier in the paper that present-day American design of boiler-house plant was productive of long continuous operating periods, reflecting a high degree of reliability. In Table 13 are given the operating statistics relative to the boiler units of the Waukegan station of the Public Service Co. of Northern Illinois. The units are of the cross-drum type, stoker-fired, the largest having a normal evaporation of 200 000 lb. per hour. The operating steam pressure is 635 lb. per sq. in. (gauge) at a total temperature of 750° F.

The principal particulars of the boiler plant for No. 3 station unit are set out below:—

Steam pressure	635 lb./sq. in. (gauge)
Steam temperature	750° F.
Evaporation	200 000 lb./hour
Boiler-heating surface (single-pass design)	14 369 sq. ft.
Water-cooled side walls heating surface	730 sq. ft.
Superheater heating surface	2 608 sq. ft.
Economizer heating surface ..	7 053 sq. ft.
Air-heater heating surface ..	90 000 sq. ft.
Grate area	467 sq. ft.
Furnace volume	6 260 cub. ft.

It will be noted from Table 13 that the adoption of water-cooled walls for the boilers of unit No. 2 reduced the outage period for repairs compared with unit No. 1, and that the total outage periods for the boilers in unit No. 3, in which all combustion chambers are water-cooled, is only about the same as that of unit No. 1, although the service hours are about 2½ times greater.

Operating steam pressure ..	250 lb./sq. in. (gauge)
Operating steam temperature	700° F.
Heating surface of boiler ..	26 470 sq. ft.
Water-heating surface in furnace, i.e. side walls, arches, apron walls and slag screen	3 014 sq. ft.
Convection superheating surface	3 520 sq. ft.
Superheating surface in side walls	1 010 sq. ft.
Air-heater heating surface	39 700 sq. ft.
Combustion chamber volume	22 000 cub. ft.

Combustion equipment:—Pulverized-fuel vertical firing.

Fig. 7 shows graphically the load and service curves of unit No. 20, at the Colfax power station of the Duquesne Light Co. from April 1927 to September 1927. The principal particulars of this unit are as follow:—

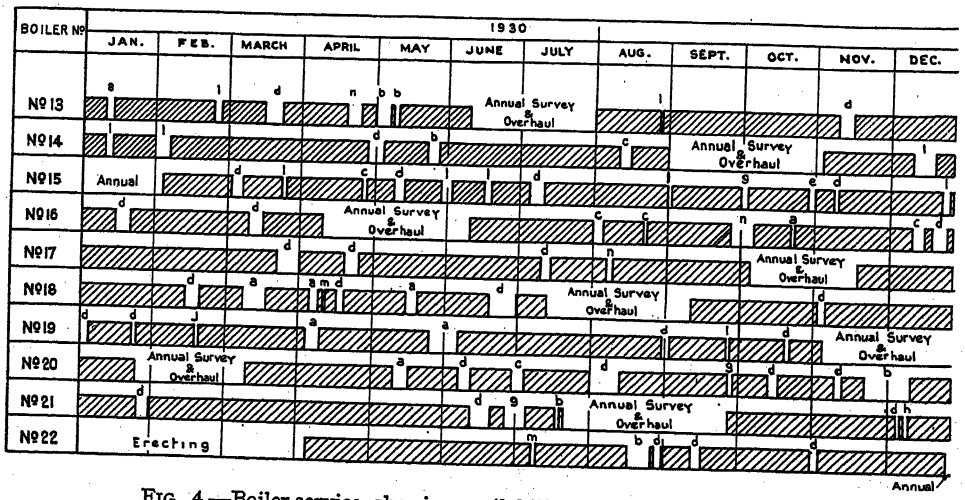


FIG. 4.—Boiler service, showing availability and outage periods.

Boiler	Babcock and Wilcox cross-drum type
Heating surface of boiler	27 680 sq. ft.
Water-cooled surface in furnace ..	2 104 sq. ft.
Superheater heating surface	5 657 sq. ft.
Air-heater heating surface	13 000 sq. ft.
Combustion chamber volume	17 050 cub. ft.

Combustion equipment:—Pulverized-fuel vertical firing.

In the *Transactions of the American Society of Mechanical Engineers* (1928, vol. 50, p. 83) there is a paper of interest relative to this subject, entitled "Some Operating Data of Large Steam Generating Units," by H. Kreisinger and T. E. Purcell.

Data in graphical form showing the operating record of various large units are given, and the liberty has been taken of extracting some of those data for inclusion in this paper.

Fig. 5 shows the load and service curves of unit No. 2 of the Fordson plant of the Ford Motor Co. one year after the boiler was put in service—1st April to 30th September, 1927.

Fig. 6 shows the load and service curves of unit No. 4 of the Fordson plant since the unit went into service—May to September, 1927.

These units, after being remodelled, were much discussed and are familiar to most engineers. They are Ladd water tube, 5-drum type, and the principal particulars are as follow:—

FACTORS IN DESIGN AFFECTING RELIABILITY AND OPERATION.

In the remarks which follow it is not intended to discuss in detail the underlying principles of boiler design. Such a discussion is outside the scope of this paper. All that the author has attempted to do is to criticize what appear to him—from an operating engineer's point of view—to be the more important aspects of the subject. It is intended to deal separately with each component of plant.

TABLE 12.—*Boiler Unit Steaming and Outage Periods for* 1930.

Cause of outage and number of hours lost (see Fig. 4).	Boiler No. 13	Boiler No. 14	Boiler No. 15	Boiler No. 16	Boiler No. 17	Boiler No. 18	Boiler No. 19	Boiler No. 20	Boiler No. 21	Boiler No. 22
Total steaming hours	4 893	4 194	5 365	4 506	4 355	4 363	5 042	4 494	4 096	3 627
(*a*) Superheater, failure of element	87	nil	nil	35	nil	59	144	182	nil	nil
(*b*) Superheater, failure of element to header joints	292	113	nil	nil	nil	367	111	499	72	198
(*c*) Superheater, failure of studs securing elements to headers	nil	123	116	326	nil	nil	nil	148	nil	nil
(*d*) Brickwork, combustion chamber, failure or finish of useful life	210	270	512	655	558	713	561	753	468	374
(*e*) Forced-draught fans, mechanical repairs addition to annual overhaul	nil	nil	103	nil	nil	nil	nil	nil	nil	nil
(*f*) Forced-draught fans, electrical repairs additional to annual overhaul	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil
(*g*) Induced-draught fans, mechanical repairs additional to annual overhaul	nil	nil	154	nil	nil	196	nil	68	218	nil
(*h*) Induced-draught fans, electrical repairs additional to annual overhaul	nil	nil	nil	nil	nil	nil	nil	nil	57	nil
(*i*) Coal-preparation plant, repairs necessitating boiler outage	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil
(*j*) Combustion chamber ash screen, tube renewals	nil	nil	nil	nil	nil	nil	18	nil	nil	nil
(*k*) Combustion chamber water walls, tube renewals	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil
(*l*) " Birdnesting " of generating tubes and/or slagging of ash screen	104	163	428	nil	nil	nil	30	nil	nil	nil
(*m*) Boiler mountings, repairs necessitating boiler outage	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil
(*n*) Boiler pressure parts, including mud boxes and interconnecting headers from drum to water walls, repairs necessitating boiler outage	116	nil	nil	64	42	68	nil	nil	nil	37
Annual examination and overhaul, outage hours	1 184	1 530	804	1 511	1 114	1 483	1 300	1 109	1 680	174
Total hours boiler unit was available for service	6 767	6 561	6 643	6 169	7 046	5 964	6 596	6 001	6 265	7 977
Availability factor,* per cent	89·3	90·9	83·5	85·1	92·1	82·0	90·8	90·2	89·3	92·0

* Availability factor $= \frac{\text{Total hours available for service}}{\text{Hours in year—Annual examination outage hours}} \times 100.$

TABLE 13.—*Boiler Operating Record (January* 1929 *to November* 15, 1929) *of the Waukegan Power Station of the Public Service Co. of Northern Illinois. All Stoker-fired Boilers.*

Station Unit No.	1			2			3			
Boiler unit No.	1	2	3	4	5	6	7	8	9	10
Hours banked	2 976	32 55	2 860	1 995	2 379	2 279	429	546	257	636
Hours in service	2 185	1 513	1 633	4 200	3 548	3 384	5 252	4 326	5 066	4 600
Hours stand-by	2 120	2 455	2 689	1 242	1 470	1 693	1 580	2 227	1 915	1 934
Hours for repairs	375	433	474	219	259	300	395	557	478	484
	Stokers operated on cold air. Units fitted with side- and rear-wall water boxes.			Stokers operated on air at 350° F. Units fitted with side- and rear-wall water boxes and refractory-covered water-cooled side walls.			Stokers operated on air at 330° F. Completely water-cooled combustion chambers and arches. Units 7, 8, and 9 have water-cooled surfaces refractory-lined, and unit No. 10 has metallic blocks on rear wall.			

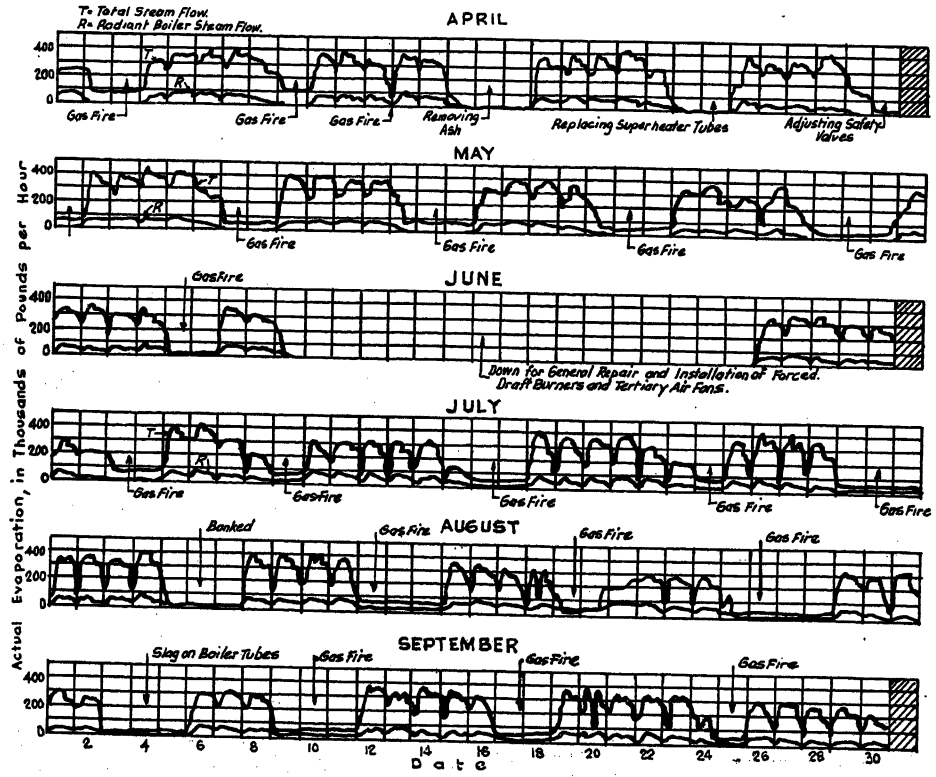


FIG. 5.—Load and service curves of unit No. 2 of the Fordson plant one year after boiler was put into service, 1st April to 30th September, 1927.

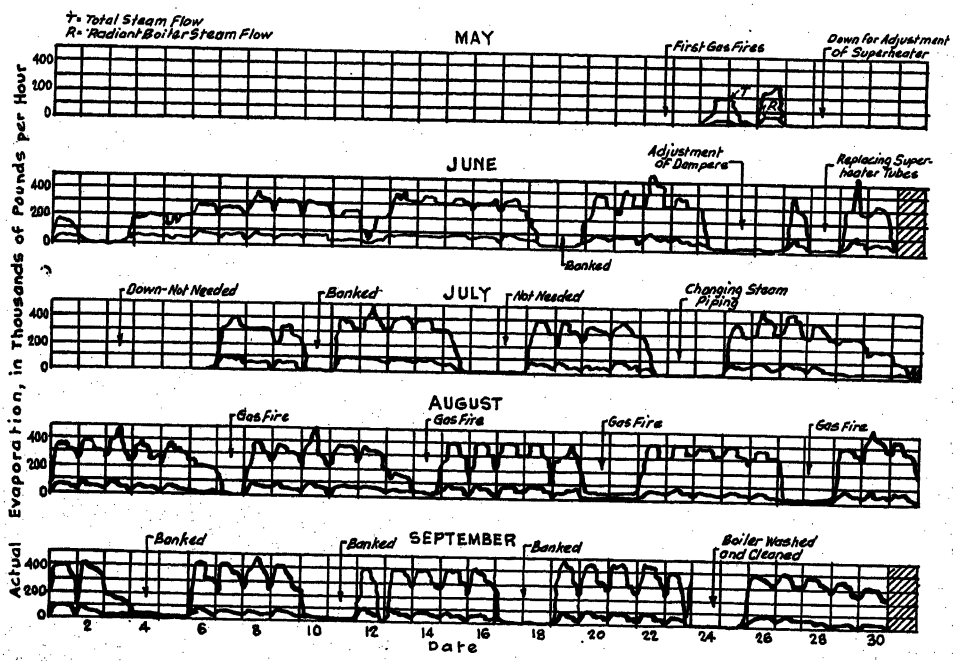


FIG. 6.—Load and service curves of unit No. 4 of the Fordson plant, since unit was put into service in May, to 30th September, 1927.

Water-Heating and Evaporative Parts (Boiler and Economizer).

The question of materials and workmanship for the pressure parts of boiler units built for pressures and temperatures in common use calls for little comment, since they are taken care of by regulations and specifications drafted to a definite code. Actual failures of boiler or economizer parts due to defective material are rare in service, and where failures have occurred the cause has been traced to other sources, usually feed-water conditioning. The same remarks concerning rarity of failure apply to workmanship on pressure parts.

There is a tendency in modern design towards higher rates of evaporation per square foot of heating surface, which, coupled with the increasing rates of heat liberation per square foot of grate area in the case of stoker-equipped units and the development of turbulent burners in the case of pulverized-fuel-fired units, results in a combined plant occupying considerably less room per unit of steaming capacity than was the case a few years ago. A slight saving in the first cost of boiler-room buildings is accomplished with plant based on such design. This tendency in design has, however, another result. It necessitates high gas velocities with multiple gas passes and consequent high fan power. It produces an increased tendency towards " birdnesting " in the first bank of generating tubes, incurs dirtier heating surfaces for a given service period and increases the total maintenance costs. Further, this design of boiler plant gives a steep efficiency curve, and control is difficult and critical. If high thermal results are to be produced over long operating periods a more highly skilled class of labour is necessary than that usually available for power-station boiler-plant operation. It is within the author's knowledge that plants following this design have only met their guarantees by being operated on special coal and controlled by very skilled experts for the 6 or 8 hours' normal load output called for under the conditions in the usual type of specification.

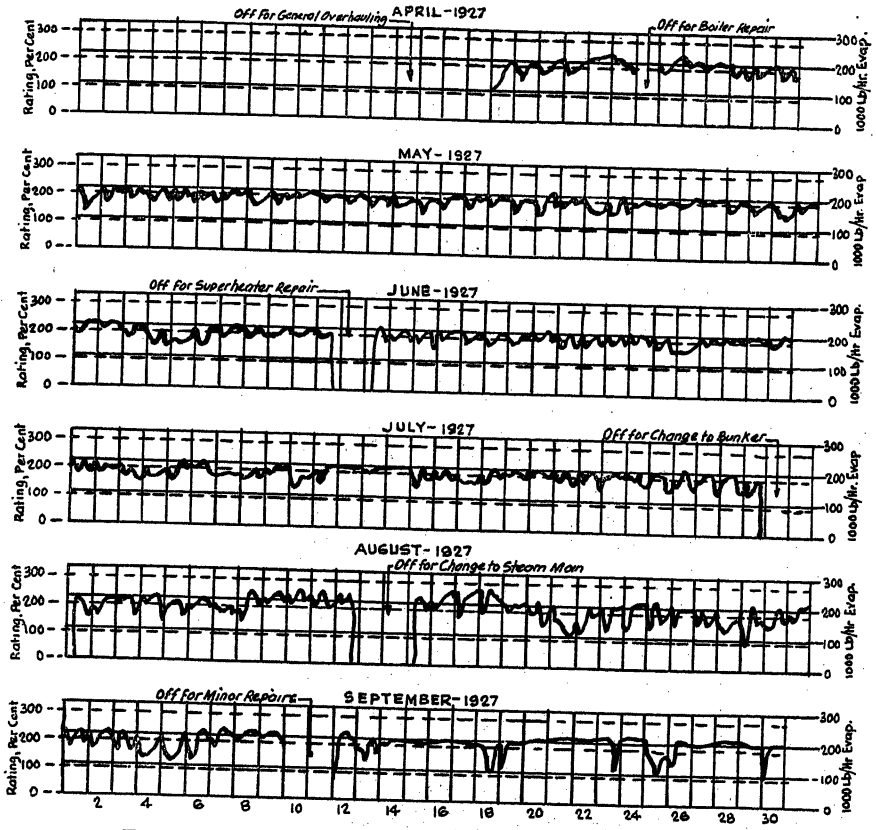


Fig. 7.—Load and service curves of unit No. 20, Colfax power station.

The existing designs of boiler unit in common use are not suitable for development for high heat-transfer rates. High rates of heat transfer or water evaporation per square foot of heating surface can only be efficiently—and, what is more important, economically—effected by radiant heat. The performance of existing designs can only be improved by the adoption of water-walled combustion chambers and by making the unit as broad as possible so as to present the maximum surface of water tubes to the furnace. Further improvement in heat-transfer performance necessitates radical departure from existing forms of design, and one phase of this development results in practically all the boiler-heating surface becoming a water-tube cage surrounding the furnace. Such a design has limitations, inasmuch that in its present state of development it can only be adopted in conjunction with pulverized-fuel combustion equipment.

Reliability and high thermal efficiency over long operating periods can be assured if, when new boiler plant is specified, a generous apportionment of heating surface is called for. Definite figures cannot be laid down to be applicable to all cases, since these figures will be influenced by the extent to which water cooling of the combustion chamber is employed and by the feed-water heating arrangements. In general, however, the average rate of evaporation per square foot of total water-heating and evaporating surface at normal load should not exceed 5·5 lb. per hour. If this heating surface is then correctly presented to a combustion chamber of ample and correct design it is possible to produce a unit having a flat or nearly flat efficiency characteristic between 0·80 normal load and 1·20 normal load. This means that not only can the unit be operated for long periods at a thermal efficiency closely approaching that obtainable under test conditions by the average intelligent operator, but also overload can be taken and carried without unduly forcing any part of the equipment. Further, it is possible to adopt a single—or at most a double—gas pass arrangement giving low-velocity gases and a minimum of fan power. Also, less fly ash, etc., is carried and deposited in the gas passes, and, since the gas velocities can be kept low, grit extraction can be largely effected by suitable gas duct arrangements between economizer and air heater and before the gases reach the induced-draught fans. In fact, it is the author's opinion that with correctly designed stoker-fired boiler plant, including the stack design, no special apparatus for grit extraction should be necessary.

" Birdnesting " in the first bank of water tubes can prove a troublesome source of boiler outage. No definite reason can be put forward as to the cause, but factors affecting the growth of " birdnesting " are the changes in velocity of the gases leaving the combustion chamber, the fusion temperature of fly ash, distribution of furnace temperature, and the CO_2 in the combustion chamber gases. It is becoming recognized that the change in gas velocity across the area mentioned should be gradual, and this can be accomplished by staggering or altering the pitch of the tubes. A development of this arrangement is shown in Fig. 8, where not only are the first rows of tubes pitched wide vertically (the horizontal pitch is 8·0 in.) but the headers are flattened across the first four rows and doors provided on the casing to facilitate local hand lancing should growth of " birdnesting " begin.

Associated with boiler-heating surface is the question of maintenance of cleanliness over long periods, and every power-station boiler unit is now equipped with apparatus for this purpose. In the majority of cases, soot-blower operation, if it is to be fully effective in the maintenance of clean surfaces and low exit gas temperatures, is necessary at least three times in 24 hours.

The introduction of high steam pressures, necessitating more costly equipment and the complication of high-ratio pressure-reducing valves for soot-blower services, has turned the attention of engineers to the question of utilizing compressed air for this purpose.

Compressed air for soot-blowing on a full-size scale has been in operation for some time on the boiler units of the Columbia station of the Columbia Power Co., U.S.A. A full description of the results obtained from this equipment is contained in a paper by R. J. Mathias and is published by the National Electric Light Association of the United States of America (N.E.L.A.).* The conclusions given in that paper are that compressed air for soot-blowing purposes is entirely successful and shows a saving of 27·6 per cent of the cost of blowing soot with steam. Operation of the equipment is similar in every way to that of the steam apparatus, and maintenance has been no heavier. The operation of the system has proved economical and has justified its installation at Columbia.

This question of soot-blower equipment is a very

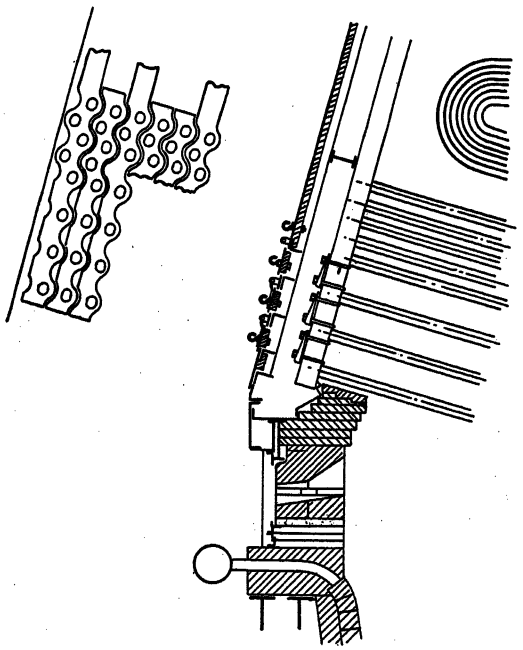


FIG. 8.—Variation in pitch of lower boiler tubes to form an " anti-birdnesting " screen and flattening of headers for hand-lance cleaning.

important one from the operating engineer's point of view, and the author feels that, in this country at any rate, the correct application of soot-blowing apparatus is a long way from finality. In many cases boiler units are equipped with possibly double the number of blowers necessary, in the hope that sheer weight of number of blowing positions will keep the unit clean. These blowers may be found with their blowing arcs arranged without any consideration to gas flow. From experience, the author recommends that all blowers should operate in the same direction as the gas flow.

In the design of blower equipment for a given size of boiler unit there is a tendency towards meagreness, particularly in the size of service piping to the various elements, with consequent increased pressure-drop and reduced efficiency in cleaning.

* See References at end of paper.

Superheaters.

The superheater is becoming more and more the most vulnerable section of the boiler unit. The demand for higher operating steam temperatures on the part of turbine designers is necessitating the location of the superheater in a temperature zone where the tube metal has to operate with a very small temperature safety margin. At the temperatures existing in this zone the liability to failure due to burning, particularly during pressure-raising, light-load or banked conditions, is great. Further, the superheat temperature demanded is often such that tube metal temperatures of 900° F. must be safely carried, which means that under ordinary conditions of operation tube metal temperatures of 1 000° F. and over are likely, possibly only for short periods, but nevertheless with very detrimental results. This causes not only outer surface burning but also, owing to the molecular reduction of the steam, oxidation of the inner tube surfaces.

In addition to the risk of failure from these causes the superheater designer is faced with the further problem involved by creep characteristics at elevated temperatures. The margin of temperature between safe and dangerous conditions is becoming so increasingly small that definite and separate control of superheat temperature may be a necessity of design in the near future. This aspect of the problem is discussed in a paper by K. Baumann, entitled "Some Considerations Affecting the Future Development of the Steam Cycle."*

These remarks relative to superheater pressure-part temperatures apply with almost equal emphasis to the materials and methods of support and suspension. Even with these increased temperatures, suspension systems are practically similar in design and construction to those employed when less arduous conditions were standard. The life of hangers, suspension beams, supports, etc., is, in the experience of the author, very unsatisfactory. If reliability of these components is to be obtained, then a radical departure must be made from existing forms of design, and some sort of air-cooled construction is indicated.

Forged steam headers are becoming standard practice both in this country and America, and the headers are now usually located outside the gas passes and inner casing.

The single-pass type of superheater is in the majority in the United States, and it is also gaining in favour in Britain.

In America superheater design is concentrating on the development of tube metals suitable for the higher ranges of temperature, and, while research in this country is in no way behind, tubes of special alloy steel cannot be drawn in lengths sufficient to fashion one complete superheater loop.

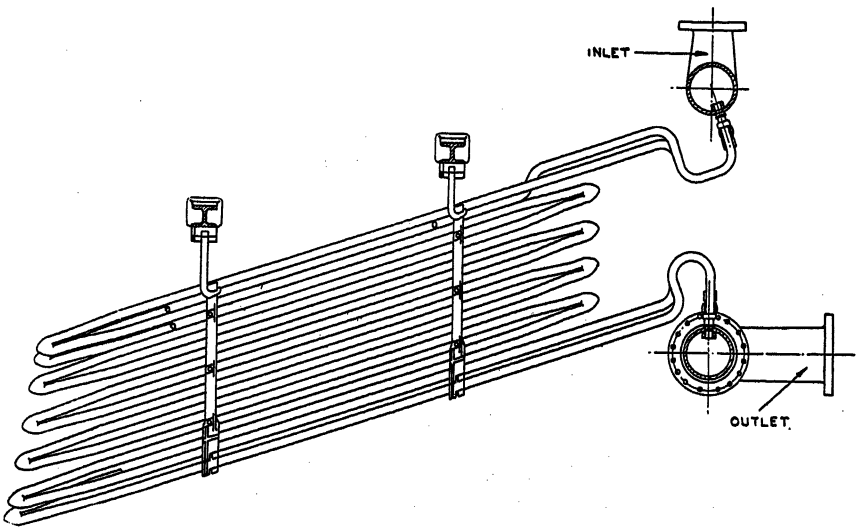


Fig. 9.—Cross-section of single-pass type superheater.

Reports from American sources indicate that the majority of the superheater troubles in that country are due to burnt tubes, and there are also complaints of insufficient drainage facilities to pass sufficient steam for tube-cooling purposes during pressure-raising or light-load conditions. Complaints have also been reported of the heat and water waste, particularly on large boiler units, necessary for tube-cooling purposes under the conditions stated in the preceding paragraph.

In Table 12 it will be noted that the majority of the boiler outage hours were due to superheater troubles, and some details of these should prove of interest. Fig. 9 shows the constructional details of the superheaters in the installation referred to, and also gives the principal particulars. The two principal troubles met with have been the failure of tubes and the failure of the studs which secure the elements to the header. The specified steam temperature was obtained at the outset and there has been no adjustment of heating surface.

The tube failures have always occurred on the last return leg of the element and on the section between the two hangers, though there have been one or two instances of failure at the last return bend. In all cases

* *Proceedings of the Institution of Mechanical Engineers*, 1930, vol. 2, p. 1305.

TABLE 14.

Temperatures Recorded by Thermo-couples on Superheater Elements of No. 14 Boiler Unit during Pressure-Raising.

		SOUTH SUPERHEATER												
Time	Gas	South superheater Element 12		South superheater Element 10		South superheater Element 8		Gas	South superheater Element 6		South superheater Element 4		South superheater Element 2	
		Front	Back	Front	Back	Front	Back		Front	Back	Front	Back	Front	Back
11.30	575	135	400	160	415	155	390	700	168	—	160	420	175	530
11.40	830	225	695	225	685	225	645	865	220	—	208	660	215	710
11.50	820	225	785	215	785	245	745	860	240	780	212	710	225	750
Noon	885	195	785	205	795	205	765	895	205	755	198	735	205	765
12.10	960	240	860	248	875	250	845	925	238	830	265	820	305	835
12.20	895	315	900	290	900	275	870	915	325	850	448	860	340	855
12.30	920	335	865	325	800	318	865	930	388	830	510	855	368	840
12.40	950	630	900	370	950	370	880	930	400	845	635	890	390	865
12.50	875	730	880	425	930	410	855	890	425	800	692	880	405	850
1.00	955	745	950	750	945	468	888	930	470	855	715	900	670	895
1.10	935	788	955	795	950	755	910	915	625	890	750	900	710	850
1.20	850	760	830	770	830	775	820	885	745	785	732	795	705	780
1.30	910	692	895	708	900	685	900	855	682	865	690	910	655	900
1.40	1 045	768	955	790	930	770	920	1 070	780	910	750	935	735	965
1.50	1 165	760	1 015	785	1 000	760	995	1 190	782	895	755	1 030	745	1 060
2.00	1 200	790	1 060	820	1 030	790	1 030	1 210	810	1 010	790	1 050	770	1 070
2.10	1 260	780	1 090	800	1 040	770	1 040	1 280	800	1 000	770	1 060	760	1 110
2.20	1 290	750	1 110	780	1 060	750	1 060	1 320	780	1 020	770	1 110	750	1 140
2.30	1 290	760	1 110	780	1 060	750	1 070	1 300	780	1 000	760	1 120	760	1 160
2.40	1 300	755	1 135	780	1 040	755	1 090	1 350	790	1 035	760	1 130	760	1 185
2.50	1 335	765	1 125	785	1 075	765	1 075	1 340	805	1 025	775	1 110	775	1 160
3.00	1 325	750	1 120	780	1 065	750	1 060	1 325	785	1 000	760	1 080	760	1 140
3.10	1 320	760	1 140	785	1 060	760	1 055	1 325	795	990	765	1 100	765	1 135
3.20	1 325	750	1 135	780	1 065	750	1 065	1 335	785	1 050	760	1 080	755	1 145
3.30	1 325	755	1 135	785	1 065	755	1 075	1 335	785	1 000	765	1 115	760	1 160

Drains kept full open until unit went into service.

the faulty section has been swollen and punctured and it has carried evidence of excessive temperature. The effect of the excessive temperature was confined to the gas side of the tubes, the internal surfaces being clean and free from evidence of any form of action.

The conditions under which the superheaters were operated were fully investigated. During pressure-raising and under banked or exceptionally light load conditions the customary practice was to utilize the superheater drain valves to discharge condensate only, and as far as possible to minimize steam discharge in an effort to conserve make-up water. During pressure-raising, however, when in the early stages considerable condensation occurs, it was customary to keep the superheater drain valves about a quarter open. The result of all the investigations made culminated in altered methods of pressure-raising and operation of superheaters during banked and light-load conditions. The superheater drain valves are now kept full open during pressure-raising, and are operated during light-load or banked conditions to maintain a flow of steam through the superheater. Since the introduction of these latter operating methods no further tube failures have occurred.

During the time this trouble was being investigated the failure of element-securing studs was prevalent, and the work of investigation was arranged with the solution of both problems as the end in view. One section of the work necessitated a knowledge of the tube metal temperatures in the superheater under operating conditions, as it was felt that an analysis of such temperatures, particularly during pressure-raising conditions, would provide some evidence to assist in determining the cause of stud and tube failures. Thermo-couples were therefore connected to a number of the elements on each superheater. These couples were located two on each of the selected elements, one being on the swan neck in the header casing and the other towards the far end of the last return leg, i.e. where it would be in the maximum temperature zone. In addition, four further couples were located in the gas path beneath the superheater but above the first bank of water tubes. A series of tests was carried out under different methods of pressure-raising, and the temperatures were recorded every 10 minutes. The figures obtained during one of these tests are set out in Table 14.

It will be noted that the temperatures recorded by the rear element couples are high, almost excessive, and are

TABLE 14—(*continued*).

Temperatures Recorded by Thermo-couples on Superheater Elements of No. 14 Boiler Unit during Pressure-Raising.

North Superheater															
North superheater Element 2		North superheater Element 4		North superheater Element 6		Gas	North superheater Element 8		North superheater Element 10		North superheater Element 12		Gas	Boiler steam pressure	Boiler output
Front	Back	Front	Back	Front	Back		Front	Back	Front	Back	Front	Back			
														lb./sq.in.	lb./hour
105	345	155	480	140	450	630	190	460	170	440	185	480	600	—	—
220	580	220	730	215	720	755	220	750	225	685	225	740	800	—	—
220	740	218	820	215	810	820	208	845	215	780	215	810	830	—	—
235	835	220	870	210	845	835	208	880	217	820	208	870	870	—	—
275	845	260	900	265	900	860	275	940	330	890	310	940	920	—	—
395	905	360	940	400	950	900	448	975	495	935	520	965	925	—	—
570	755	568	945	580	955	875	585	970	595	940	635	975	930	130	—
640	930	645	955	650	965	888	655	975	665	950	710	980	950	172	—
687	930	690	950	695	960	905	705	970	710	950	762	975	925	222	—
705	915	725	950	735	955	905	732	975	738	950	783	980	950	310	—
715	900	727	905	755	900	890	755	890	763	900	805	915	900	365	—
722	810	738	830	742	810	855	740	810	750	810	778	820	840	370	—
672	795	675	840	685	845	905	685	855	688	840	708	885	918	370	—
618	660	622	810	655	850	1 000	670	840	665	825	695	885	1 045	375	On load
645	690	680	890	695	940	1 100	710	925	700	920	735	980	1 150	375	
690	710	700	900	720	950	1 140	730	940	740	940	750	990	1 150	378	—
670	690	680	920	700	970	1 200	700	960	700	950	720	1 020	1 240	380	125 000
660	790	680	940	700	1 020	1 270	710	990	720	1 000	730	1 050	1 310	377	130 000
670	760	690	970	710	1 030	1 270	720	1 020	720	1 020	750	1 070	1 320	380	140 000
670	720	695	980	720	1 045	1 300	730	1 030	722	1 030	755	1 085	1 320	380	135 000
680	780	710	950	730	1 000	1 300	750	995	730	995	765	1 065	1 345	380	135 000
668	810	695	940	715	990	1 290	730	980	725	985	745	1 050	1 340	377	135 000
670	760	695	945	715	990	1 310	728	985	720	985	750	1 045	1 345	377	140 000
655	765	688	950	705	995	1 280	720	995	710	1 050	740	1 055	1 345	380	140 000
670	735	700	965	720	1 020	1 285	730	1 000	725	1 015	760	1 065	1 360	380	140 000

Drains kept full open until unit went into service.

just below safe limits. That the safety margin is small is proved by the fact that burning still occurs on the lower ends of the element-supporting clips. The provision of a free flow of steam during pressure-raising conditions, etc., can prove a very costly business, since it results in a direct water and high-grade heat loss. This loss can be prevented and, at the same time, a greater flow of steam provided for protective purposes by an arrangement such as that shown in Fig. 10. The lay-out is shown diagrammatically but is nevertheless self-explanatory. It consists essentially of a saturated steam range to which all or several of the boiler units are connected. The superheater of each boiler unit is connected to this saturated steam range. During pressure-raising a supply of steam for superheater protective purposes is taken from this range, passed through the superheater and then to the main steam range. The possible lower temperature of this protective steam entering the main ranges during a short period in the initial stages of pressure-raising, and its effect on the temperature of the main body of steam, is negligible. When pressure is raised, the boiler unit is put into service in the ordinary way and the protective steam supply then shut off. A further advantage is that such a system provides protective steam for banked and light-load conditions.

The problem of the failure of element-securing studs has been more obscure. When the plant was installed the superheater elements were secured to the headers by the type of stud shown in Fig. 11. These studs had the following analysis and characteristics:—

Analysis.

	Per cent
Carbon	0·490
Silicon	0·340
Sulphur	0·032
Phosphorus	0·040
Manganese	1·020

Physical properties.

Tensile strength	50 tons/sq. in.
Yield point	35 tons/sq. in.
Elongation in 2 inches	16 per cent
Izod impact (minimum)	40 ft.-lb.
Reduction in area, not less than ..	40 per cent

When the plant had been in service about a year one of these studs failed on the cross-section shown, releasing the two elements which it held. That failure

was followed at intervals by others on different superheaters, though certain units seemed to be more prone to stud failure than others. The outstanding feature of all these stud failures is that up to the time of writing

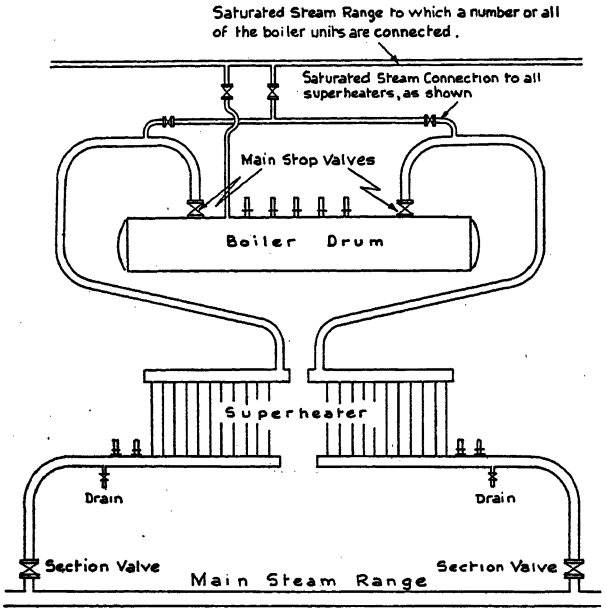


FIG. 10.—Saturated-steam connections for protection of superheater during pressure-raising, banked, or light-load conditions.

these notes all the failures have been confined to studs securing the elements to the saturated steam headers. In no case has a stud failed on any of the superheated steam headers. Reference to Fig. 9 will show that in the case of both headers the bottom of the stud root is in communication with the interior of the header, the difference being that in the case of the saturated steam header the studs protrude through the bottom of the header, while those in the superheated steam header enter through the top.

The problem of these failures has been investigated from all aspects, but so far no satisfactory solution has been found. Careful measurements of header, element, steam-pipe, and boiler-section movements have been made and analysed, and the question of embrittlement from carry-over has also been investigated. The stresses in the assembly and in the stud have been calculated and examined for all the conditions met with. Alterations and modifications to the various suspensions of the headers have been tried; investigation of the temperatures involved under all operating conditions was made as previously described; failed studs have been submitted to the National Physical Laboratory for examination and report; but none of these efforts has produced a definite reason for the failure of these studs.

At this stage of the investigation it was felt, from a consideration of the collected evidence and in spite of the fact that no failures had occurred in the studs on the superheated steam headers, that the fault lay in the studs. A new type of stud was therefore designed as in the arrangement shown in Fig. 12. These were made of an alloy steel having the following analysis and characteristics:—

Analysis.	Per cent
Carbon	0·290
Silicon	0·170
Sulphur	0·027
Phosphorus	0·029
Manganese	0·440
Nickel	3·200
Chromium	0·800
Molybdenum	0·530

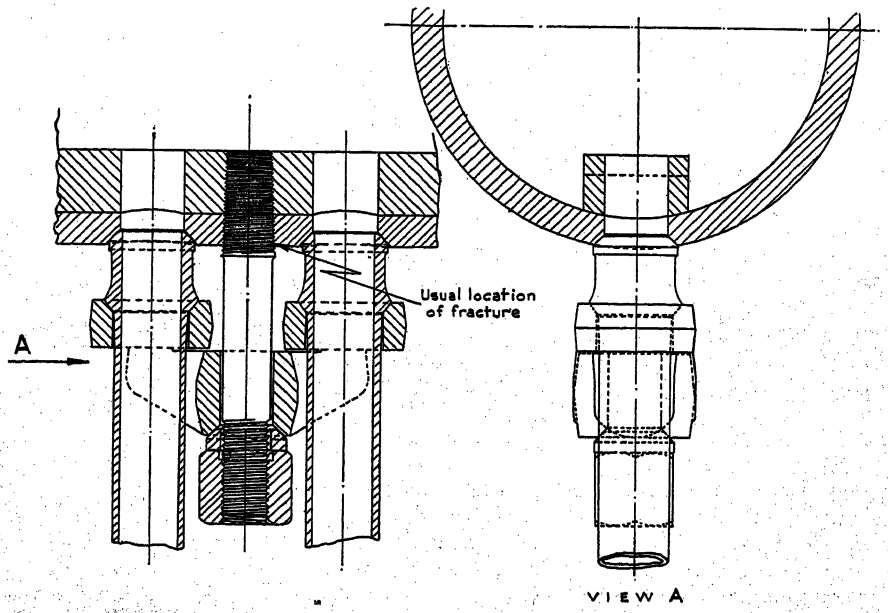


FIG. 11.—Method of securing and seating superheater elements to header, as originally installed.

Physical properties.	Per cent
Tensile strength	70–75 tons/sq. in.
Yield point	60–65 tons/sq. in.
Elongation in 2 inches ..	16 to 20 per cent
Izod impact (minimum) ..	45 ft.-lb.
Reduction in area, not less than	50 per cent
Heat treatment	Oil-hardened at 830° C. Tempered at 600° C.

Four boiler units were equipped with this new stud in the superheater headers, but reasoned opinion that faulty studs were the root of the trouble was shattered by the failure of one of the new studs shortly after going into service. The failure and the type of fracture were similar in every way to those previously experienced. This failure has been followed at intervals by further fractures of the new type of stud. In one case the fracture will be partial, while in another it will be over the full cross-section.

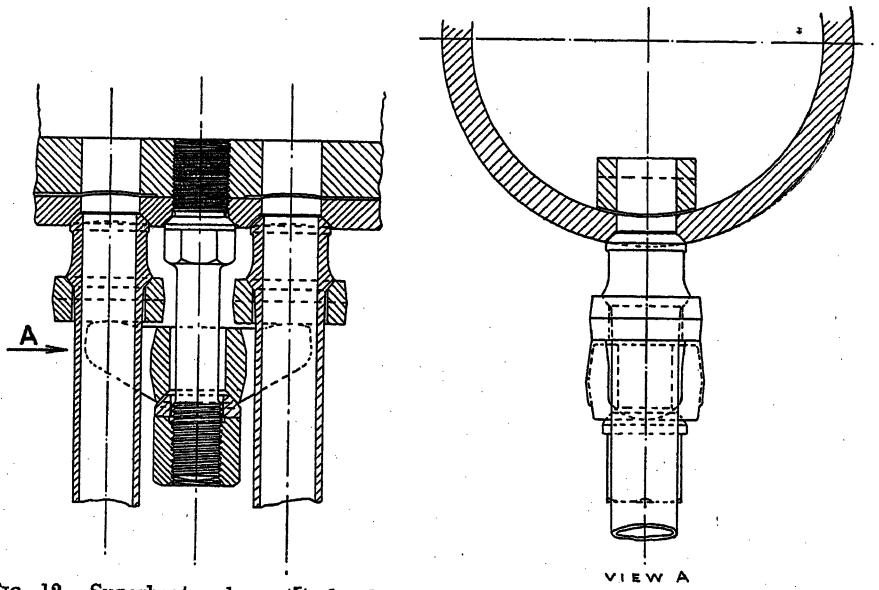


FIG. 12.—Superheater element to header assembly with altered design of securing stud.

The type of superheater is not new and untried. It is common in America and has been fully proved under modern power-station pressure and temperature conditions. The author believes he is correct, however, in stating that the superheater installation referred to is the only one either in this country or America in which the studs in the saturated steam headers enter at the bottom and protrude into the steam space. The recent work of research authorities has indicated that the range of alternating or intermittent stresses, even of very low frequency, which a steel specimen can withstand without failure is seriously reduced if the specimen is in contact with a corroding medium during the application of the stresses. The work of McAdam has shown that under these conditions even pure water must be regarded as an effective corroding agent. In the case of the failures referred to here the roots of the affected studs can be exposed to condensed steam. It should be made clear that the design of superheater header discussed here is now out of date. For modern pressure and temperature conditions the headers of this type of superheater are made of eccentric cross-section or of such a wall thickness that the stud roots do not pierce the steam space.

The modern demand for high ratings under normal operating conditions also affects superheater design. Attempts are made to get the maximum area into the usually inadequate space allocated by the boiler designer, and many modern plants have difficulty in meeting superheat temperature guarantees. If ample superheating surface is allocated in the first instance, and the incorporation of the superheater in the boiler unit carefully arranged, this component can be kept at the maximum distance from a critically dangerous temperature zone. Further, the fact that the assembly will not be cramped and inaccessible facilitates cleaning and repair work and lessens the risk of "birdnesting" in the spaces between the superheater tubes. If then, when in service, it is found that the superheat temperature is too high, a remedy is easily applied in the reduction of heating surface. It is preferable, however, that the specified superheat temperature should be slightly exceeded when the plant is first put into service, for after a very short time a coating of ash scale forms on the outer surfaces of the tubes, and this effectively reduces the heat-transfer rate and the final steam temperature. This scale cannot be removed by soot blowers, and, except on the more easily accessible outer tube rows, cannot be removed by hand cleaning when the unit is out of service.

The increasing magnitude of the problems affecting the design of superheaters for incorporation in the standard forms of boiler unit may, in the near future, result in radical alterations to the boiler unit form. At the present moment the inter-deck or inter-tubular type of superheater is in the majority, but for future development this location may prove to be too vulnerable. It would appear that the ideal location would be such that

separate and definite control is possible of the heat supplied to the superheater. This does not necessarily mean a separately fired superheater in the usually accepted sense of that term.

Combustion Chamber.

The influence of combustion chamber design on boiler unit performance has already been referred to, and the importance of correct design of this component requires no further stressing.

The principal combustion equipment and boiler plant manufacturers in this country have certainly, in recent years, realized the necessity for research work and investigation of the factors affecting scientific combustion chamber design.

Though practical experiment and the resultant performance are the final proof of the efficacy or otherwise of a given design, research work has made available formulæ applicable in general for a given combination of conditions. Very few tabulated data have, however, been published, especially in this country, but in America the pioneer work of Wohlenberg, Bailey, Murray, Kreisinger, etc., has been put on record and is outstanding. The lack of published data in this country is principally due to the problem of combustion chamber design being much more complicated than it is in the majority of cases in America. There the problem is considerably simplified by the fact that a plant may operate for the whole of its life on one particular coal varying in chemical, physical, and combustion characteristics between very narrow limits.

The development in combustion chamber design for coal-burning boiler plant and for all the accepted types of combustion equipment is due in a large measure to, and is most marked from, the introduction and initial rapid adoption of pulverized-fuel firing. Briefly, the history of practical development is as follows:—

Combustion chambers for the early installations of pulverized-fuel plants followed closely the accepted design for stoker-fired furnaces. The walls were of solid refractory, and the furnace was fired by straight-shot burners giving a long flame. To prevent this flame licking the walls, and, further, to give room and the necessary time element for complete combustion, the chamber was of necessity large and heat-liberation rates were correspondingly low, 10 000 B.Th.U. per cub. ft. per hour being seldom exceeded. Rapid deterioration of refractory compared with the life of refractory obtainable with stoker-fired furnaces led to the development of the turbulent burner, giving a short flame which could be kept clear of surrounding brickwork. It was hoped from this trend in design that not only would more complete combustion be effected but that the combustion chamber volume could be considerably reduced. There was a limit, however, to this reduction as a result of increased heat liberation and increased furnace temperature, and rapid deterioration of furnace walls was still an adverse feature of these early installations. The next phase consisted principally of research work for the development of a refractory capable of existing over a reasonable life under these arduous conditions, and, though refractories were found which would reasonably resist the fluxing action of molten ash, no refractory would satisfactorily resist the scouring action. Further, these high-melting-point refractories were very prone to "spalling."

The introduction of the hollow air-cooled combustion chamber wall followed and proved successful with low heat liberation rates; that is, with long-flame burners and large-volume combustion chambers. Such design had a further advantage in readily lending itself to the introduction of secondary air to the furnace. A reduction in combustion chamber volume with this type of wall construction and incorporating turbulent short-flame burners was not successful.

The result of further research work led to the introduction of a certain amount of wall cooling by means of water tubes, and further experimenting, during which a large number of valuable data have been tabulated, was carried out with designs incorporating walls partially cooled to combustion chambers employing entire water cooling by means of tubes on all walls. In the stoker-fired furnace field similar work was being done, but with a slightly different end in view, and, about the time these experiments were being conducted on pulverized-fuel combustion chambers, water boxes for the preservation of the lower courses of the side walls of stoker-fired settings were finding favour. Realization of the valuable heating surface provided by water-cooled walls was immediately appreciated, problems connected with circulation were overcome, and this feature of modern design became standard practice. Three types of water-cooled combustion chamber construction are in general use—the plain tube, the fin tube, and the block-covered tube.

The design of any combustion chamber is governed by the predetermined mean furnace temperature to be employed and the temperature at which the gases will be discharged to the boiler heating surfaces. The design will also be influenced by the type of combustion equipment and the class of fuels on which such equipment will be operated. The most important factor affecting design is the fusion temperature of the ash, and it is this factor which makes combustion chamber design in this country a more complicated problem than in America. The fusion temperature of the ash in a combustion chamber utilizing refractory in any degree fixes definitely the maximum mean furnace temperature that can be economically employed, and also becomes a prominent factor in the extent of cooling to be adopted. The difficulty of the problem will be appreciated when it is borne in mind that, to quote only one instance, the fuels supplied to the generating station with which the author is associated vary in ash fusion temperature from a lower limit of approximately 1 800° F. upwards.

A further factor affecting combustion chamber design is the type of duty to which the plant will be applied. Briefly, the use of full furnace water cooling will permit the highest possible heat release and the use of small furnace volume, but flexibility in operation will be limited, and this design can only be successfully applied to boiler units which are to be normally operated at, say, from 0·75 load to 1·20 load. Further, from the published data on the subject, this type of design actually increases the total boiler heating surface required. The possibility of utilizing a smaller volume can also negative

any potential advantages, since such smaller volume reduces the time element available for completion of combustion. It follows that with this type of design for either stoker or pulverized-fuel firing a high degree of turbulence is necessary, produced in the latter case by turbulent burners, and in the former case special overhead air booster fans may be necessary.

On the other hand, the full refractory-lined combustion chamber can be operated efficiently—from a combustion point of view—over a wide range of boiler loadings, but, as previously stated, such a design is impossible under the arduous conditions of modern service. The use of refractory, with our present limits of preheated air temperature, has also obvious beneficial effects on combustion. It has been mentioned that combustion air temperature for stoker practice is limited, but for pulverized-fuel firing the upper limit of such temperature can be very much higher, and the fully water-cooled furnace offering a reasonable degree of flexibility in operation then comes within the range of serious consideration. Further, the individual boiler units of the modern large station are seldom routine-operated outside the load limits stated.

A consideration of the subject leads one to the conclusion that for the bulk of the coals utilized for power-station steam generation in this country, a combustion chamber combining water-cooling and refractory will give the best all-round performance. The degree of cooling to be employed and the area to be water-cooled and refractory-lined, and the location of these areas, are governed by the factors previously mentioned. The refractory can either be in the form of separate walling or of special construction, forming part of the water tube assembly.

British practice in combustion chamber design, particularly for travelling-grate stokers, has been responsible for the development of the archless type of setting, and this, coupled with the water-cooling of the vulnerable sections of the side walls, cannot but result in a considerable decrease in refractory maintenance costs. The work done in connection with water-cooling of arches has been noteworthy, and it is of great interest to note how few the troubles have been.

In the development of combustion chamber design, particularly for stoker-fired furnaces, the point has not yet been reached where refractory can be entirely eliminated, and the size of the modern combustion chambers for power-station practice is becoming such that the refractory wall construction requires careful treatment from a mechanical point of view. Special types of construction have been developed, but even these can be a source of danger when operated on low ash fusion point coal and they become heavily loaded with slag. These remarks also apply to curtain wall constructions in the upper zone of certain types of pulverized-fuel furnaces.

The trend in design is towards the elimination of arches or flat roofs. This section of the combustion chamber in both travelling-grate and vertical-fired pulverized-fuel furnaces has been one of the weakest points in the boiler unit, particularly under the conditions of modern service, and a life of over 4 000 hours for the nose assembly of the arch is the exception rather than the rule.

The reliability of the combustion chamber is capable of considerable improvement, and a construction no less reliable in every way than that of the remainder of the boiler unit is desirable.

Though combustion chamber design has now reached such a degree that its relation to the other sections of a boiler unit can be closely calculated, there is still a tendency to produce a cramped construction. In the design of this component there is more need for generosity than in any other part of the unit; this is particularly so in the case of stoker-fired furnace design. In the furnace of pulverized-fuel equipment combustion is more evenly effected, and a more even heat distribution throughout the combustion chamber is obtained, but in the furnace of stoker-fired equipment much wider variations from the mean temperature occur and result in high-temperature zones and local hot-spots on the furnace envelope. Height, or rather distance, from the firebed to the boiler section water tubes is of the first importance, but height without volume will prove unsatisfactory.

The geometrical form of the combustion chamber is a factor of importance both from the point of view of combustion and the incorporation of water tubes. The nearly cubical form employed for pulverized fuel has remained standard and lends itself to the assembly of straight water tubes in the high-temperature zone. The form of furnace used in stoker practice, more particularly for travelling grates, has undergone many changes during the last few years, but recent development points to the wider adoption of the cubical form of construction with only a small ignition arch. It is suggested that where water-tube walls are employed they should slope slightly inwards towards the top in the section carried in the furnace, to ensure that the hot tube surfaces are continually water-swept. With vertical tubes, and particularly with tubes inclined outwards towards the top of the chamber, there is danger of the hot surfaces which are continuously generating steam not being fully water-swept, and if scale-forming salts are present in the boiler water blistering and puncture will occur. Feed- and boiler-water control, however, has reached a high degree of efficiency in most modern plants, but, on the other hand, many of these very plants utilize a boiler water artificially given a definite causticity and also carrying other reagents chosen to minimize embrittlement. Tri-sodium phosphate or sodium sulphate is commonly used for this latter purpose. With sodium sulphate in a boiler water and the possibility of calcium hydrate entering the system from softening or evaporating plant, the formation of the hard scale of calcium sulphate is practically certain. Further, it has been the author's experience that the deposition of this salt will occur in the water tubes of the combustion chamber, and it requires very little scale in this high-temperature zone to result in blistering and puncture. It is noteworthy that water-wall tubes which have failed from this cause have shown no tendency to rupture. In every case of this type of failure within the author's experience the only evidence has been a very small hole in the blister.

Failure of tubes can also occur due to overheating if the water walls are not designed and constructed to give

a free and definite circulation under all conditions of load, and no attempt should be made to economize on headers and risers. In fact, in one American design, to ensure satisfactory operation of the heating surfaces incorporated in the combustion chamber this section was constructed practically as a separate boiler. The cross-section of a composite unit of this type is shown in Fig. 13.

The variable and low ash-fusion temperature of many of the rough slack coals used for power-station steam generation in this country has already been referred to, and while not strictly associated with combustion chamber design the question of the discharge and disposal of this ash is always an important feature in planning a new plant. Development of the slag tap furnace for pulverized-fuel plants has shown considerable progress in America, though the principal difficulty of chamber-bottom construction has not yet been satisfactorily overcome. It would appear, however, that the characteristics of our coals lend themselves admirably to this type of combustion chamber construction for pulverized-fuel plants, and if successfully developed to meet our conditions would offer an economic solution to many difficulties.

Combustion Equipment.

The most marked progress in mechanical-stoker practice has been in the development of the travelling-grate type. Ten years ago a boiler unit with an evaporative capacity of 60 000 lb. of steam per hour would have necessitated the installation of three separate stokers. To-day a boiler unit having an evaporation of over 200 000 lb. of steam per hour can be equipped with a stoker of the travelling-grate type which is virtually a single machine.

With the tendency to increase the rates of evaporation per unit of heating surface in the boiler there has also been a tendency for increased rates of combustion per square foot of grate area. The improvement in design and construction of the travelling-grate stoker and the improvement in combustion chamber design has made these higher combustion rates possible, but, as in the case of the other components of the boiler unit, there is a tendency in stoker design towards excessive ratings.

Combustion rates as high as 80 lb. of coal per sq. ft. per hour have been obtained, but in spite of the outstanding improvements in stoker practice this type of equipment has its economical limitations, and these high ratings, even if accompanied by reliability and ease of control, can only result in excessive maintenance costs. Further, the stoker equipment as part of a boiler unit cannot be considered separately but must bear some proportionate relation to the remainder of the unit, and unless a departure is made from the generally accepted boiler unit form the small, compact, high-duty travelling-grate stoker must be considered in conjunction with highly rated evaporative and heat-transfer surfaces. For ease of control, reasonable flexibility, a wide margin of efficient operation, and a capability to meet comfortably overload conditions and operate in emergency on high combustion rates, the modern type of travelling-grate stoker should be installed to be normally operated at combustion rates between 30 and 40 lb. of coal per sq. ft.

One phase of development has resulted in considerable alteration to the stoker construction. Up to the time when large grate area was asked for in one machine it was customary to construct the stoker on a carriage which could be withdrawn from the boiler setting for repairs to inaccessible parts of equipment. With the increased width and length of stoker this type of construction is no longer so easily applicable, and modern design usually provides for erection *in situ*. Unless considerable forethought is given there is the possibility of accessibility being sacrificed, and repair or examination of the interior and rear of the stoker then involves considerable dismantling work.

The increase in stoker size, accompanied as it was by the development of high preheated-air temperatures, brought problems involving the expansion of the grate surface and travelling-gear components, and the author feels that these problems have not been solved as satisfactorily as they might have been. The grate surface components must have flexibility and freedom to expand and move in every direction and yet be sufficiently secure to retain uniformity of position. It is preferable that the grate surface itself should only carry the firebed and should not take any of the driving strain. This should be effected by means of robust chains, fully flexible and with ample provision for expansion. Where the grate surface does carry the driving load the links or section of the grate so loaded should be of suitable material. A further provision is necessary in ensuring that failed or broken grate sections, links or louvres can be readily replaced without putting the machine out of service. The construction of the framing, supports, cross-members, etc., should be such that a broken or distorted grate section, link or louvre cannot foul and produce disastrous results. No interior moving parts, driven either from the moving grate surface or by external means, should be employed for the removal of riddlings and fines. These can be discharged without such risk-engendering complications.

During the last few years the design of driving gear for travelling-grate stokers has been considerably improved. Ten years ago the majority of manufacturers considered four speeds ample, and a gearbox providing that number of ratios was usual practice. It has been customary British practice to provide for the electrical driving of travelling-grate stokers, and, that being so, the ideal would appear to be a speed-reduction equipment of the "infinitely" variable-ratio type. This end can be approximated electrically, but the first cost of this type of equipment is high, and modern practice is usually satisfied with a gearbox giving 8 progressive ratios. These ratios are not always as happily arranged as they might be, and while the first four steps can be coarsely pitched without detriment to operation the top four ratios, on which the stoker will be normally operated, should be progressively closer.

There is one marked difference between American travelling-grate stoker practice and ours; no ash-dumping gear or clinker dams are fitted, nor are they thought necessary, and, in spite of this, American figures show that the carbon-in-ash loss can be maintained at

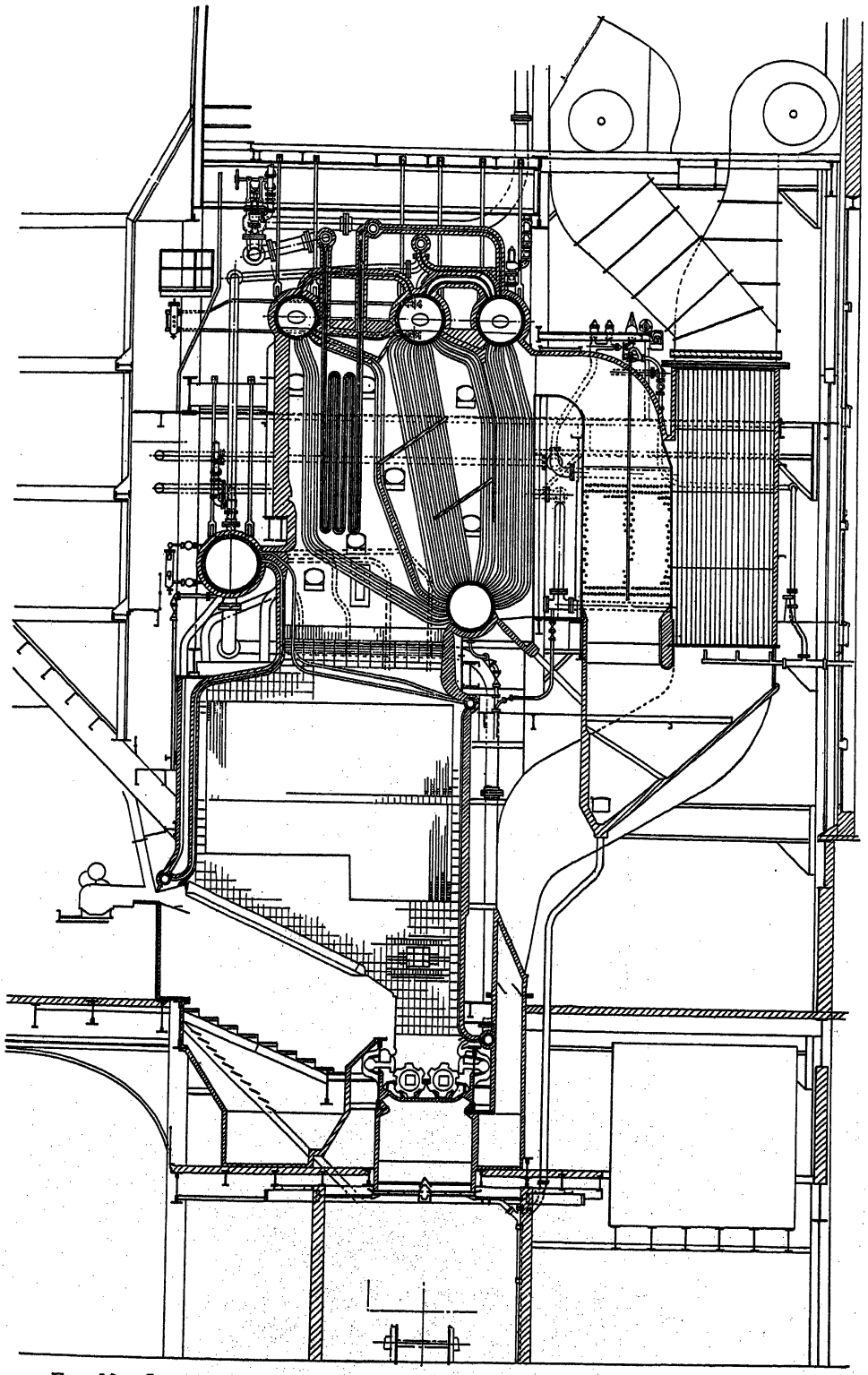


FIG. 13.—Cross-section of boiler unit (Delray power house No. 3, Detroit Edison Co.).

less than 1·0 per cent of the heat balance. The elimination of this item from the various types of British machine would reduce a maintenance item that can be considerable. This can only be accomplished, however, by improvement in the rear sealing of the stoker and the giving of greater consideration to the controls for the maintenance of a square burning firebed. Another difference in the practice of the two countries is in the design of the dead plate. In the American type of machine there is practically no dead plate at all, and in the author's experience the dead-plate area of certain design of British stokers, especially if these are operated on high-temperature air, can be considerably reduced with beneficial results to ignition control.

The tendency towards the employment of still higher-grade heat in bled steam for feed-water heating is resulting in the stoker designer being called upon to provide a mechanism that will operate at high temperature and yet remain cool; that is, cool in comparison with the other temperatures in the stoker zone. The difficulty of satisfactorily operating travelling-grate stoker plant at high temperatures is one of the principal obstacles in modern design and can be the result of factors other than high air temperature, but the accumulated experience of the past few years is being fairly successfully applied.

Travelling-grate stoker design of a few years ago provided for the combustion air being fed to the compartments or a wind box built integral with the stoker and carried between the top and return grate surface. This design, in conjunction with restricted combustion chamber volume, resulted in excessive grate temperatures.

It is now customary to enclose totally the stoker, and pass all the air for combustion through the whole stoker assembly. This, in conjunction with the advantages accruing from the use of generously proportioned combustion chambers, has enabled stokers to operate satisfactorily at grate temperatures cooled to the neighbourhood of 350° F. The method of conducting the air to the firebed, especially between the air heater and the stoker, should be given as much consideration as any other important section of equipment. Too often ducting—and this includes gas ducting—consists of sheet-metal work which would disgrace a tinsmith. The principles of air and gas flow should be studied in the lay-out of all ducting, and, needless to say, it should be gas- and air-tight. These may seem trivial points, but too often such grounds for criticism are found. The air should be fed to the stokers on both sides through ports of large area, and the control of air to the firebed should be effected by louvre dampers immediately beneath the active grate surface. In addition to providing control along the length of the stokers, these dampers should also provide transverse control in order that a square firebed may be easily carried.

The various main dampers in the air and gas ducts are important details of combustion equipment, and here again existing design is poor. These dampers should be of such a design—preferably multi-vane—that the velocity of the gas or air over the cross-section of the duct at this point is reasonably uniform and retains its uniformity, though varied in value and/or quantity. The air velocity either in the ducting or entry to the stoker should not exceed 5 000 ft. per min. at any point.

Considerable experience in the application of high preheated air temperature for combustion has been gained from the operation of No. 1 boiler house at Barking. It should be noted that this was the first large plant in this country in which economizers were eliminated. Each boiler unit is equipped with an air heater of approximately 17 000 sq. ft. heating surface, supplying preheated air to twin stokers of approximately 300 sq. ft. total grate area at temperatures around 450°–550° F. in the case of 8 boiler units and 400°–450° F. in the case of the other 8 boiler units. In considering the following remarks relative to the stoker performance of this plant it must be borne in mind that the design is now out of date and cannot be compared with modern practice. The remarks, however, should be of interest since they form a small record of pioneer work.

The plant has been operated on over half a million tons of coals, consisting principally of Northumberland Rough and mixed slacks, washed and unwashed, and, included in that tonnage, a considerable quantity of Yorkshire and Nottingham slacks and smalls, and Lothian and Fifeshire washed peas, singles and doubles. During the coal strike of 1926 a quantity of foreign coals was used, consisting of German lignites and brown coal and Spanish slacks. A great amount of investigation work was done by everyone concerned, but naturally it cannot all be detailed here.

Summarizing the salient features observed, it was found that with air temperatures in excess of 400° F. it was impossible to maintain the minimum grate temperature below that value, and the process of combustion and the behaviour of the firebed in general were influenced in a manner not previously experienced. It was noted that when operating conditions were set to obtain efficient combustion, i.e. with excess-air values of the order of 40·00 per cent, the temperature of the grate rose to over 500° F. The time taken to attain this temperature depended upon the speed of the grate, coal quality, firebed thickness, and combustion chamber pressure. Tests with many different coals showed that the minimum critical grate temperature was in the neighbourhood of 400° F., though with some coals operation was possible up to 500° F. These temperatures refer to those measured at the front of the grate exposed to the atmosphere and after having been exposed to any natural cooling effect when coming over the ash and riddling hoppers.

When the grate surface reached the above temperatures a very quick change occurred in the behaviour of the firebed. Starting in the ignition zone the firebed formed itself into lumps which were termed "cauliflowers." These gradually assumed a dull red appearance, except around their edges, at which points intense combustion was apparent. These points were admitting the only air to the firebed, and, as there was a very large amount of excess air here, this fact, in conjunction with the loss of temperature from the "cauliflowered" areas, resulted in the arches becoming cooled, and things generally became unmanageable. As the firebed split up, the CO_2 content of the flue gases fell from 13 or

14 per cent to less than 6 or 7 per cent. The boiler output fell from normal to less than 25·00 per cent, and the firebeds went over to the ash pit in an unburnt condition.

Samples of these " cauliflowers " taken from the back of the grate showed complete ash round their sides, coke on top, and coke and slight ash mixed with caked coal underneath. Inside was a layer of semi-volatilized coal having the appearance of tar after setting, and in the heart of the sample was coal which to all appearances had never been inside a furnace.

Exhaustive tests were made with different arch settings, different firebed thicknesses, alterations to size and length of dead plate, alterations to method of air distribution and opening the rear of the stoker and modifying the ignition and distillation zone to draw in cold air. It was found that continuous operation could be maintained by carrying a high combustion chamber negative pressure, thus cooling the grate by air infiltration through the stoker and setting in general. Overall thermal results, of course, suffered. Cooling the grate to below critical temperature by artificial means—such as water sprays, or, as was done on one unit, by cooling fans—entirely eliminated the trouble, but in both cases the heat loss was an appreciable thermal item.

On the 18th January, 1928, a series of photographs was taken of the furnace of No. 11 boiler unit with a view to recording the effect of grate temperature on combustion. The photographs were taken over a period from 11.5 a.m. to 4.0 p.m. The camera was placed at the rear of the boiler unit, viewing the firebed of the right-hand stoker through the peep-hole of the rear inspection door. Four of these photographs are reproduced here as Fig. 14 (see Plate facing page 572).

The foregoing remarks apply entirely to the performance of one particular design of stoker. The other half of this boiler plant is equipped with a different type of grate, which operates at a lower average air temperature. On this latter installation also the same combustion phenomena were apparent, and satisfactory operation was influenced by a definite grate temperature.

Various modifications in the method of supplying air to the firebed and passing this air through both runs of the grate resulted in better operation, but it was difficult to maintain the grate surface below critical temperatures on any but one special delivery of coal. Further investigation of the problem led to experimenting with the combustion air diluted with a percentage of flue gas bled from the boiler-unit uptake. The result of this was to slow down the combustion rate in the most active region of the grate and lower the maximum temperature which the surface of the grate could reach during its travel through the furnace. With this latter modification fairly satisfactory operation is possible, but with certain coals the critical temperature of the grate is so low as to necessitate very careful operation.

From a study of this subject in general, and experience with this plant in particular, it would appear that since the temperature of the preheated air is one of the most important factors governing the grate surface temperature, satisfactory operation of travelling-grate stokers operated on the usual run of bituminous slack coals is limited to an air temperature in the neighbourhood of 350° F.

The incorporation of an air heater as part of the combustion equipment of the modern boiler unit is now established standard practice, not only because air-heater surface is cheaper than equivalent economizer surface or because of the fact that feed-water heating can be most economically effected by steam bled from the main turbines, but also because preheated air is a necessity with pulverized fuel, a recognized advantage to stoker operation, and the only means still available in modern design for the reduction of final flue-gas temperature.

The extent to which economizer surface can be replaced by air-heater surface is governed by the permissible temperature at which the gases enter the air heater. In the case of pulverized-fuel plant this temperature is governed by the materials available for the heater construction, and, in the case of stoker plants, principally those of the travelling-grate type, the upper limit of temperature is a function of the factors previously referred to.

When air heating was first applied on a reasonably wide scale to power-station boiler plant the problems involved were fairly simple. Boiler units were small, economizers, in proportion, were large, and all the air heater was called upon to do was to reduce by a few degrees the temperature of the economizer leaving gases. If it failed in service, as a general rule it could be bypassed for repair, and its loss was not felt to any great extent. In the design of modern power-station boiler plant, however, it is an important item of equipment and is responsible for a large percentage of the credit side of the heat balance. The design of the modern air heater is, therefore, of equal importance to that of the remainder of the plant. In addition to being a thermally efficient piece of apparatus it must also possess a degree of reliability equal to that of any other section of equipment, and be free from the necessity of excessive maintenance. The performance demanded from the modern air heater necessitates large heat-transfer areas, and compactness coupled with accessibility is a necessary feature without sacrifice of any of the above-mentioned requirements. Further, owing to the difficulty of cleaning the gas side of the heat-transfer surfaces by the usual type of steam blowers, the velocities should be so apportioned that under normal operating conditions the apparatus is self-cleaning. In the author's opinion the air heater should have no moving parts, and to attain efficiency of heat transfer and compactness of construction the air and gases should flow in opposite directions in thin alternate films. The construction should be such that no leakage between gas and air is possible, and no bolts or stays should be used which pass alternately through gas and air films. Further, the gas and air should have as nearly as possible straight-through paths, and no cavitation should be possible at the gas and air entries.

The usual air-heater troubles experienced in operation, apart from leakage (which should be taken care of in design), are choking and corrosion. These troubles can usually be traced to the fact that a section of the air heater is operating under dew-point condition of the

TABLE 15.

Coal-Preparation Plant Costs of American Power Stations.

Company	Cleveland Electric Illuminating Company	Detroit Edison Company	Duquesne Light Company	Illinois Power Company	Narragansett Electric Company	New York Steam Corporation	Pennsylvania, Ohio Power and Light Company
Name of station	Avon	Trenton Channel	Colfax	E. Peoria	South Street	Kip's Bay	Toronto
Pulverized-fuel system	Central	Central	Central	Central	Central	Central	Central
Class of coal	Bituminous	Bituminous	Bituminous	Bituminous	Semi-bituminous	Bituminous	Bituminous
Size of coal	Run-of-mine slack	Run-of-mine slack	Run-of-mine	Slack	--	Slack	Run-of-mine slack
Type of mill	—	Roll	Raymond 6-roll	Raymond 6-roll	Raymond 15-ton	Raymond 15- and 25-ton	Raymond 15-ton
Coal, tons per mill per hour	16·70	5·75	12·6	6·62	17·82	12·30	13·00
Total kWh/ton	16·20	23·86	16·0	25·73	13·76	20·83	17·26
Preparation Costs, Cents per Ton.							
Electrical energy*	4·86	7·16	4·8	7·72	4·13	6·20	5·18
Operation labour	3·35	6·27	2·8	2·45	6·83	11·70	4·81 }
Oil and grease	0·80	0·43	0·7	0·73	0·97	—	1·52 }
Other operating material	—	0·16	0·1	—	—	—	—
Maintenance labour	2·94	2·68	1·2	2·86	4·60	6·10	2·24 }
Maintenance material	3·97	3·94	1·2	4·92	5·67	2·70	3·00 }
Total preparation costs, cents per ton	15·92	20·64	10·8	18·68	22·20	26·70	16·75

* All based on same cost per kWh.

flue gases. This can be caused, assuming correct heater design in the first place, by prolonged operation under light-load conditions, bad distribution of air over the cross-section of the air inlet, or a faulty arrangement of gas ducting, resulting in starvation of a section of the heater. Further, even with correct air and gas distribution, corrosion or condensation and choking can occur over the cross-section of the gas exit due to seasonal or climatic low inlet-air temperatures, but this is usually covered by providing that all air is drawn from under the boiler-house roof and is therefore reasonably warm. For operation under loads lower than normal it is now customary to provide bypass arrangements, integral with the heater assembly, so that the operating temperatures never approach the dew point.

Earlier in this paper it was stated that the adoption of pulverized-fuel equipment for large power-station practice was suffering from a temporary set-back, and what the author felt to be one of the reasons for this situation was also set out.

Development in the use of pulverized-fuel combustion equipment in this country during the last two years has been very restricted, and it is to American sources that we must turn for a record of recent work. The most marked progress has been in the development of what is termed the "unit" system of application of pulverized-fuel firing to boiler plant. With both unit and bin-and-feeder systems, however, the experience gained is reflected in the improvements in milling plant and burners. Recent reports of American progress in this phase of boiler-plant practice show that for the year 1930 the construction of unit systems was more than three times that of central or bin-and-feeder systems, calculated on the total horse-power of the respective boiler plant. The unit system has much to recommend it, but the many further advantages obtainable by a combination of both unit and bin-and-feeder systems deserve serious consideration. American reports show that the total capital costs favour the unit system, and recorded conclusions state that equal performance, efficiency, availability, and operation costs can be obtained with either system, but with a saving in standing charges in favour of the unit system. With either system the cost of coal preparation is the item which usually necessitates the greatest supervision.

Table 15 has been compiled from data abstracted from N.E.L.A. Publication No. 12, 1930. It is obvious, of course, that absolute comparison cannot be made between the two systems when applied to different plants, but the record is interesting in that the majority of the central system operation figures quoted, when compared with the unit-system figures, bear out in general the previous statements.

The arrangement of fuel-preparation plant referred to as a bin-and-feeder system is a development of the original central system, in which the coal-preparation process was conducted entirely separate from the boiler plant and usually in a separate building, the product being transported to bins and feeder gear on each boiler unit. The original central system was costly, and the transport of the fuel from preparation plant to boilers was complicated and troublesome. Further, the venting of each milling system was a problem until the mills were installed close to the boilers and the individual circuits vented into the combustion chambers, either directly or via the burners or primary air system and burners.

The advantages and disadvantages of either system

TABLE 15—(*continued*).

Coal-Preparation Plant Costs of American Power Stations.

Pennsylvania Power and Light Company	Pennsylvania Water and Power Company	Union Gas and Electric Company	West Pennsylvania Power Company	Ohio Public Service Company	Pennsylvania, Ohio Power and Light Company	Rochester Gas and Electric Company		Wisconsin Public Service Company
Pine Grove	Holtwood	Columbia	Springdale	Mohoning-side Unit	North Avenue Unit	Station No. 8 Unit	Station No. 9 Unit	Bayside Unit
Central River dredge and anthracite	Central Half river anthracite half bituminous	— —	Central Bituminous	Bituminous	Bituminous	Bituminous	Bituminous	Bituminous
No. 4 brick and culm	—	—	Crushed run-of-mine	Slack	Slack	Slack	Slack	Screenings
Fuller Lehigh	Fuller Lehigh	—	Raymond	Raymond impact	K.B.	Raymond impact	Raymond impact	Hammer type
10·40	6·40	—	—	1·50	1·39	2·06	1·19	2·30
26·70	21·40	—	—	20·90	18·30	16·10	15·6	21·40
Preparation Costs, Cents per Ton.								
8·01	6·42	5·82	—	6·27	5·49	4·83	4·68	6·42
20·74 {	17·94	9·32	4·00	5·30	—	—	—	4·10
	0·69	0·75	0·65	0·06	—	0·26	0·26	0·26
9·16†	1·75	—	—	—	—	—	—	—
36·99 {	4·77	3·20	3·40	1·37	3·30	3·04	0·91	2·16
	18·27	6·24	4·50	2·49	4·20	5·12	5·17	5·95
74·90	49·44	25·33	12·55	15·49	12·99	13·25	11·02	18·89

† Drier fuel.

can be argued from many points of view, but briefly the salient factors are as follow:—

The bin-and-feeder system if installed as a complete unit for each boiler is higher in first cost than a plain, straightforward unit system employing no duplication. In such a case the operation costs of the bin-and-feeder system will be appreciable when compared with the operation costs of the simple unit system.

The bin-and-feeder system, as its name implies, involves the introduction of a fuel storage bin, fuel feeder gear, and, in addition, a cyclone to separate the milled product from the carrying medium and discharge it to the storage bin. This extra plant means that a bin-and-feeder system requires more room than a simple unit system, and since the storage bin, as a rule, has to be above the combustion chamber or burners, and the cyclone above the storage bin, extra building height is required.

On the other hand, with a single unit system to each boiler the failure of a vital part of the coal-preparation plant involves the complete stoppage of the boiler unit, and this can only be guarded against by, at least, duplication of the mills, and in some instances, where a high degree of reliability must be ensured, exhausters and other vital parts are duplicated as well. This arrangement then considerably offsets the extra head-room required for the bin-and-feeder system.

The exhauster fans on a unit system have to handle both the fuel-carrying medium and the pulverized coal. Wear on these fans is excessive, and their useful life is very much shorter than is the case with the exhausters of a bin-and-feeder system in which the carrying medium only is handled, and renewals of exhauster casing or runners should seldom be necessary.

It is the author's opinion that a bin-and-feeder system can be designed and constructed to give a greater degree of reliability to the boiler plant than is possible with any unit system. It has already been stated, and reference to Table 12 will show, that during the year reported in that table no boiler outage was caused as a result of failure or even routine outage of coal-preparation plant.

With a bin-and-feeder system the whole milling plant can be operated continuously under the best conditions, which are stable and unaffected by the boiler plant, resulting in a product of uniform fineness. With a unit system the operating conditions on the milling plant have to fluctuate with every variation of boiler load demand and every variation in combustion conditions. All mills generally used for the production of pulverized fuel have a narrow range of efficient operation, and the general performance and product of a mill vary enormously by changes in speed and in air velocity or coal quantity through the mill.

The bin-and-feeder system lends itself admirably to fuel drying in the milling system by means of bled flue gas. The same method of drying can, of course, be employed with unit mills, but since all the medium sweeping the mills goes forward with the milled product to the burners the introduction of flue gas for coal-drying purposes means that the combustion air is less rich in oxygen per unit of volume, and burner efficiency cannot be so good as with a bin-and-feeder system.

The burners of a bin-and-feeder system can be operated irrespective of milling conditions, but with a unit system every alteration to burner conditions usually necessitates alteration to the milling conditions.

The power consumption per ton of product can be slightly in favour of the unit system.

The bin-and-feeder system lends itself to a very simple form of automatic control, but a unit system can only be automatically controlled if boiler loading and combustion variables are also taken into account.

From these remarks it will be gathered that the author favours a form of bin-and-feeder system arranged integral with each boiler, with a further degree of reliability ensured by well-designed and constructed screw conveyors interconnecting the cyclone outlets. Any pulverized-fuel plant can only be a success if its designers, constructors and operators have the necessary knowledge of the subject, but granted that such a knowledge is possessed by those concerned the author feels that such a plant as he has suggested can, in operation, have the reliability of the best turbo-alternator machinery, with operation and maintenance costs lower than the equivalents in stoker-fired boiler plants.

It has already been mentioned that the design of pulverized-fuel equipment is still in an early stage of development, but criticism can be offered against the usual way in which these plants are put together. Each plant should, in its individual components and as an assembled whole, bear some resemblance to a first-class engineering product. The design of ducting, dampers, operating and control gear, screw conveyors and the smaller items of the assembly is capable of very considerable improvement.

The majority of designers and operators consider that a fineness in grinding approximately as follows is good practice and that the cost of producing a greater fineness is unwarranted:—

+ 40 I.M.M.* mesh	1·00 per cent
+ 100 I.M.M. mesh	9·00 per cent
— 100 I.M.M. mesh	90·00 per cent

The author is, however, of the opinion that this question of fuel fineness is deserving of more investigation, and that mill development can be effected to give a finer product at little or no increased cost. One argument against finer pulverization, apart from milling costs, will be the apparently increased chimney-dust emission due to the greater percentage of small particles. This argument does not now hold,

Further development in burner design is another necessary feature. At present a few of the best designs of burners have a range of operation of 2 to 1; that is to say, they can be operated efficiently from 50 to 100 per cent capacity. The majority of burners, however, do not possess such performance figures as these, and

TABLE 16.

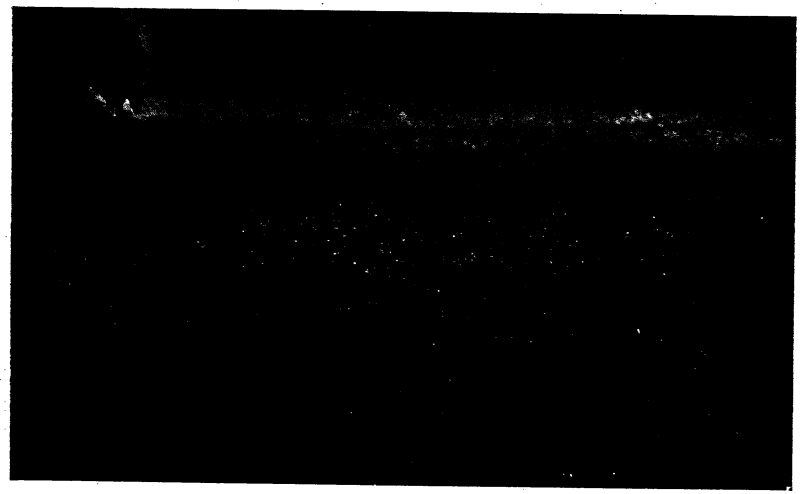
Mill Performance Data.

Date	24/6/31	26/6/31	27/6/31	29/6/31	30/6/31	1/7/31	2/7/31
Duration of test, hours	6	4	6	5	5·5	5·25	5
Average mill current, amps.	37·00	38·60	40·00	37·50	40·00	37·50	40·00
Average exhauster current, amps.	20·00	19·50	20·00	20·70	20·50	20·20	20·25
Average temperature outlet, ° F.	155	170	160	151	157	162	158
Average tons/hour throughput	12·70	14·20	13·50	13·30	14·00	15·10	16·60
Pressures :—							
Air casing (Negative (water gauge))	4·25	4·50	4·50	4·30	4·50	4·25	3·80
Mill .. (Negative (water gauge))	10·50	9·75	10·75	10·00	9·75	9·00	9·25
Mill uptake (Negative (water gauge))	14·75	14·00	14·75	14·90	14·75	14·00	14·00
Drop across mill (water gauge) ..	10·50	9·50	10·25	10·60	10·25	9·75	10·20
Speed, r.p.m.	93·70	99·00	99·00	99·00	97·90	97·50	98·00
Number of pendulums	6	6	6	6	6	6	6
Raw coal :—							
Class of coal	Bowers fines; Bentinck; Newbiggin; N.R.S.	N.R.S.	N.R.S.	N.R.S.	Bentinck; Bothal; Newbiggin; N.N.S.	Welsh R.N.S.; N.N.S.	Bentinck; Welsh R.N.S.; Bothal; Newbiggin
Total coal milled, lb.	172 480	127 008	179 340	150 000	172 400	178 700	186 400
Moisture	10·02	8·89	8·89	9·08	7·74	8·84	6·65
Pulverized fuel :—							
Classification + 40 I.M.M. ..	1·30	0·50	0·70	1·70	1·00	0·70	2·10
+ 100 I.M.M. ..	7·10	7·90	7·10	9·80	8·70	7·60	11·30
— 100 I.M.M. ..	91·60	91·60	92·20	88·50	90·30	91·70	86·60
Moisture, per cent	2·51	2·11	2·60	2·93	3·13	3·42	3·36
Pyrites :—							
Total pyrites bled, lb.	—	—	1 313	1 117	1 076	1 330	890
Pyrites in coal milled, per cent ..	—	—	0·733	0·745	0·626	0·746	0·477
Float/sink test, percentage of pyrites floated	—	—	3·770	2·630	3·530	7·280	4·560

N.R.S. = Northumberland rough slacks. N.N.S. = Northumberland nutty slacks. R.N.S. = Rubble and nutty slacks.

* Institution of Mining and Metallurgy.

To face page 572.



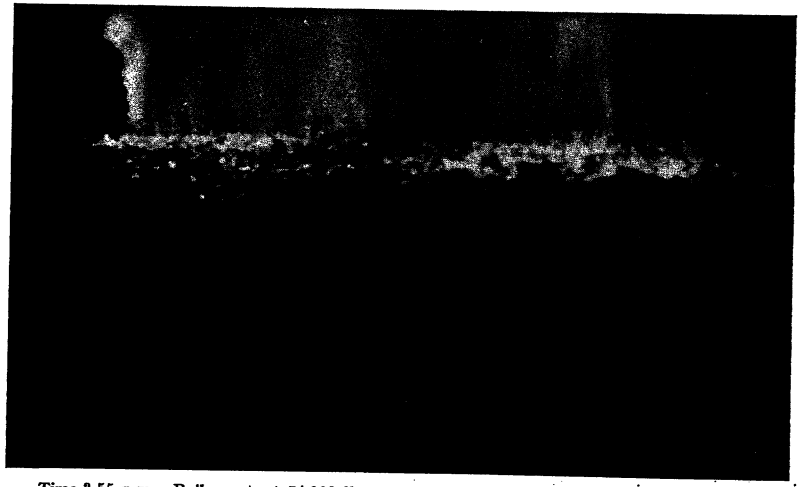
Time 11.10 a.m. Air temperature 450° F. Boiler output 82 000 lb. per hour. CO_2 13·6 per cent. Water-cooling shut off. Fires clear.



Time 1.45 p.m. Air temperature 450° F. Boiler output 70 000 lb. per hour. CO_2 11·5 per cent. General "cauliflowering."



Time 2.30 p.m. Boiler output 80 000 lb. per hour. CO_2 13·6 per cent. Fire continuing to clear at ignition end, and "cauliflowering" travelling on grate towards camera.



Time 3.55 p.m. Boiler output 74 000 lb. per hour. CO_2 13·3 per cent. Fire almost clear.

FIG. 14.—Effect of grate temperature on combustion.

[Photos: D. Charles.

flexibility can only be obtained by installing a number of burners per boiler unit. This does not infer that a boiler unit should be equipped with only one burner.

The author has had a considerable experience with what is one of the largest pulverized-fuel-fired boiler plants in Europe—not without its troubles—but in spite of troubles and difficulties, which have been or are being successfully overcome, it is his opinion that a correctly designed and applied pulverized-fuel equipment offers considerably more advantages than mechanical stoker plant when considered in conjunction with the

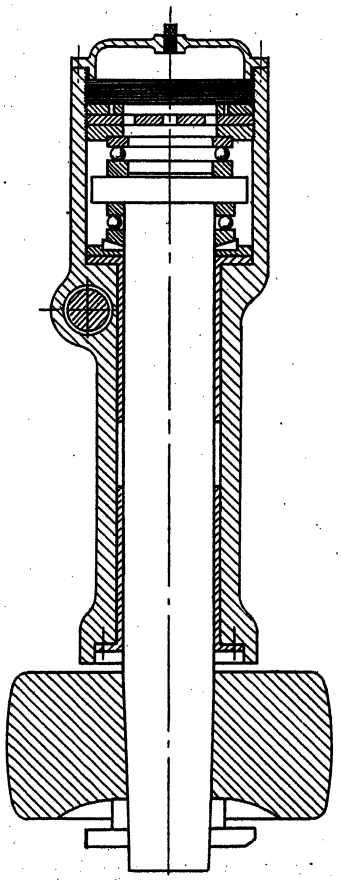


FIG. 15.—Modified Raymond mill pendulum assembly.

large boiler unit. With pulverized-fuel plant higher sustained thermal efficiencies can be obtained over long operating periods than is possible with mechanical stoker plant. Pulverized-fuel equipment is much more easily operated a greater degree of flexibility is obtainable and the control of the combustion process is more accurate and definite than with stoker plant. Pulverized-fuel plant can be easily and efficiently operated on a much wider range of coal classes and qualities than can stoker plant. Again, assuming correct design and application, pulverized-fuel equipment gives to the boiler plant a greater degree of reliability than does stoker plant.

The increasing load on supply areas in this country, the increased unit size of the turbo-alternator and the national "grid" becoming an accomplished fact, give an ample reason for a reconsideration of boiler-unit capacities. The adoption of pulverized-fuel plant makes possible the installation of these larger boiler units, and the author suggests that for the modern generating station of around 300 000 kW capacity an economic case can be made for the adoption of pulverized-fuel-fired boiler units having individual capacities in the neighbourhood of 500 000 lb. per hour. This size and type of plant offers advantages in reduced capital cost on plant and buildings, simplicity in lay-out and operation, and—not the least important—a very considerable saving in operation labour.

Mention has been made throughout the paper of the performance of the pulverized-fuel plant at a large representative British station, and a short history of the behaviour of the coal-preparation section of this plant should prove of interest. In the early life of the plant, operation and results were very unsatisfactory. The mills suffered from excessive vibration, and the average life of mill bull-rings was in the neighbourhood of 15 000 tons, while the life of a set of six rollers was around 6 000 to 7 000 tons. The plant was, and is, operated entirely on Northumberland rough slack coals, which are recognized as being of a very abrasive nature and high in pyritic content.

Early experiments showed that by reducing the speed of the mills from approximately 101 r.p.m. to 98 r.p.m. very much smoother running was obtained. The speed was reduced by inserting resistors in the rotor circuit of the mill motor, and as a result of these experiments all the mill motors were similarly equipped and tapping points provided in each resistor, giving a choice of four reductions of speed to 91 r.p.m. This reduction in speed had a marked effect, however, on the fineness of the pulverized fuel. At that time, and prior to the reduction in speed, the fuel classification was approximately:—

+ 40 I.M.M. mesh	2·50 per cent
+ 100 I.M.M. mesh	14·00 per cent
− 100 I.M.M. mesh	83·50 per cent

After the reduction in speed the average fuel classification was somewhat as follows:—

+ 40 I.M.M. mesh	4·00 per cent
+ 100 I.M.M. mesh	20·80 per cent
− 100 I.M.M. mesh	75·20 per cent

Naturally, combustion troubles followed, and smoke control was critical. Slagging of the ash screen and "birdnesting" of the boiler generating tubes were also fairly prevalent.

Further experiments showed that by reducing the number of pendulums in the mills the fineness of the powdered fuel could be increased to an acceptable value, but at the cost of output. The improvement was, however, so marked that in spite of the lowered output the pendulums in each mill were reduced from 6 to 3. The average fineness rose to around 88·00 per cent through a 100 I.M.M. mesh, with figures frequently above 90·00 per cent on the same screen basis.

While these experiments were in progress a simple device for application to Raymond mills for the extraction of pyrites was fitted to one mill and put under test. This device was developed by the Ashington Coal Co. for similar but smaller mills at their colliery plant. The

possible success of this device was evident from the start, and all the mills were equipped with at least two of these pyrites traps, adjusted to suit this size of mill.

During this time mill circuit venting and cyclone performance were unsatisfactory and affected boiler operation. Various modifications were therefore made and tests carried out. A rearrangement of the mill ducting to bypass a proportion of the air and gas across the air ports and fuel bed to increase the suction in the base of the mill and improve the pyrites-trap performance was a further betterment which brought more satisfactory results. The improvement in venting, the increased efficiency of the main cyclone, and the ducting modifications to the mill have made possible the use of the full number of pendulums, and the figures given in Table 16 are typical of the performance obtained at different mill "throughputs" from about 70·00 per cent full load to 25·00 per cent overload.

Further to these modifications and improvements, which were principally connected with operation, the mechanical performance of the plant was investigated, and in addition to improving detail equipment, modifications were made to parts of the mill design.

The majority of the mills are equipped with the old type of grease-lubricated pendulum, and at the outset lubrication troubles resulting in seized pendulum shafts were many. The weight of the roller was supposed to prevent the pendulum from rising, and thrust plates were also fitted between the bush housing and the top of the roller. These suffered from heavy wear, and the pumping action of the shaft filled the lower journal with powdered coal. Further, grease flowed to the bushes very spasmodically, and what did flow could only be displaced by coal-dust-laden air or coal dust alone worked up between the shaft and bush. These troubles were overcome by the design of pendulum shown in Fig. 15. The lubrication of the central spindle also occasionally gave rise to anxiety, and this was remedied and the mills were equipped with the system shown in Fig. 16.

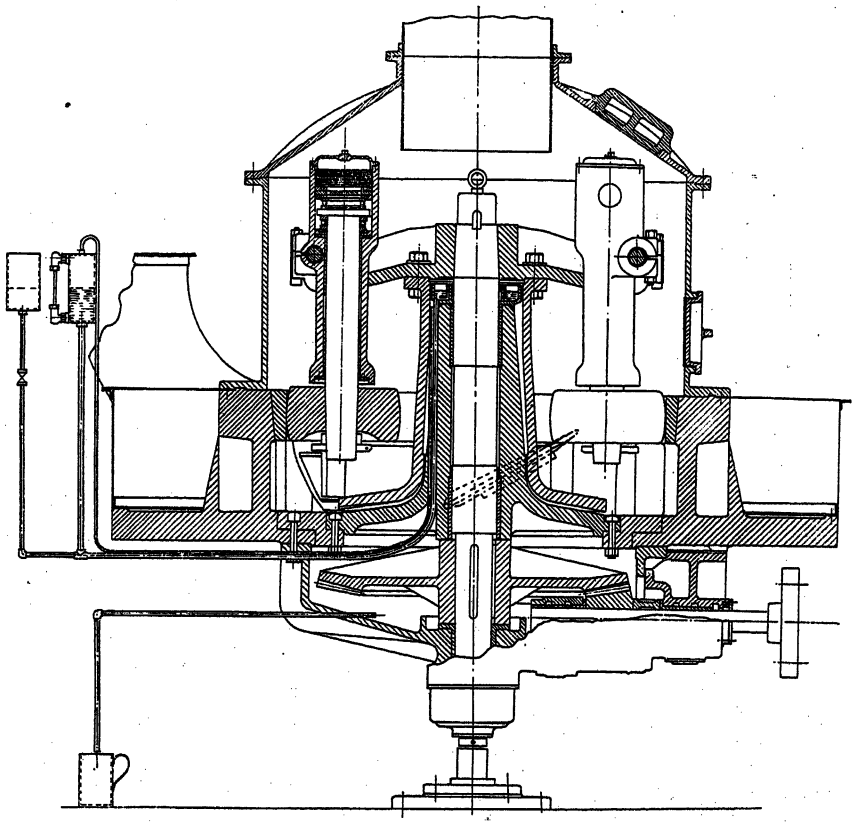


FIG. 16.—Method of lubricating central spindle of Raymond 15-ton mill.
Oil flows via central spindle to gearcase, and overflow from this is returned to head tank.

With the plant in its present condition a bull-ring life of over 40 000 tons has been obtained. Rollers have, on mills fitted with full modifications, given a useful life of over 20 000 tons per set, and it is confidently expected that these figures will be a common average for the whole of the plant when the work of modification and improvement is completed. The time taken to effect these improvements may seem to have been long, but it must be borne in mind that investigation and testing work could not be final on short-period trials. Further, during all this work the boiler plant has consistently carried the bulk of the load on the station.

The Raymond type of mill is capable of being made as a first-class engineering job, and is ideally suitable

for the grinding of highly abrasive coals. An analysis of the performance of this type of mill, basing the estimate on present labour and material costs, shows that an overall figure of 3d. per ton of coal milled may be possible for operation, lubrication, maintenance labour, and material.

FLUE GAS, DUST, AND SULPHUROUS FUME EXTRACTION.

During the last few years the elimination of dust, and to a lesser extent the elimination of sulphurous fumes, from boiler-plant flue gases before these gases are discharged into the atmosphere has become a question of increasing importance, not only for new plants under consideration but also for those already in operation.

The nature of the problem and the fundamental principles governing the design of plant for dust extraction or sulphur elimination have been the subject of many papers presented before our learned societies. Further, most engineers in general, and power-station engineers in particular, are familiar with the increased attention now devoted to chimney emission by local authorities, etc. From the recurring prominence of the subject in other than technical affairs it would almost appear that the whole question of chimney emission may soon be governed by more stringent ordinances than hitherto.

The present prominence given to this subject is one result of the development and use of highly-rated, high-gas-velocity boiler plant employing short chimneys and high fan power. Further, owing to unfortunate litigation, adverse Press publicity has helped to spread entirely wrong impressions.

Considering apparatus for the extraction of dust only, such apparatus must possess certain features. It must be simple; it must be capable of operating efficiently over a wide range of gas volume and dust concentration; it must contain a minimum of moving parts; it must be automatic in operation and require a minimum of operating attention; its capital cost must be comparable with that of the other items of boiler-house equipment; its operating and maintenance costs must be low; it must occupy a minimum of space; it should be capable of installation before the induced-draught fans and it should not unduly increase the boiler fan power; and the caught dust should be discharged to a disposal centre at a minimum of cost. Development of plant for dust extraction is proceeding rapidly along three general lines, and at present there are available and in general use those of the cyclonic type, those employing a water film or water sprays, and those employing an electrostatic screen.

The problem of sulphurous fume elimination is separate and distinct from the problem of dust extraction. The development of plant for this purpose in particular is being ably handled in this country by the London Power Co. and the Manchester Corporation Electricity Department, and reports of the progress made by the former undertaking have already been published.

In connection with dust-extraction plants, one great need is a reliable and standard method of testing the performance of this class of equipment. Various methods are in use, but each possesses inherent sources of possible large errors. Further, the measurement of dust or grit particles presents many difficulties. Mesh screens do not take into consideration the specific gravity of the particles, and, on the other hand, elutriation methods alone cannot be used as a standard. Further, there appear to be at least half a dozen screen meshings in use, and each is considered a standard by some authority.

Two years ago the Chimney Emissions Committee of the Electricity Commission set up a small technical sub-committee to investigate and report upon what has been done or is being done towards the elimination of grit emission in this and other countries. The author has the honour of serving on these Committees, and he feels that any further expression of opinion on his part relative to this subject in the present paper would be anticipating any report that may be made by the Chimney Emissions Committee.

The problem of the emission of grit, and to a lesser extent the emission of sulphurous fumes, can be viewed from an entirely different standpoint from that considered so far in this paper. The possible benefits derivable from the use of clean coal, carrying negligible ash and sulphur contents, are recognized by most engineers. These benefits affect more than chimney emission, for the use of such a fuel offers possibilities of a considerable saving in operation and maintenance in connection with the cleaning of gas passes, combustion chamber upkeep and repair, and the handling and disposal of ash. Clean coal at an economic price offers possibilities in connection with pulverized-fuel plant, but unfortunately the use of very low-ash coal on high-temperature preheated-air stoker equipment involves metallurgical difficulties in connection with the grate surface.

ARRANGEMENT OF BOILER PLANT.

The lay-out of a boiler plant should be such that the following factors are fully satisfied. There should be ample natural light available in as many parts of the plant as possible, particularly on the operating floor. The assembly of the plant should be such that all the major operation can be easily affected from one level, and all auxiliary plant should, as far as possible, be located on this level. The principal individual components should be so arranged that they are readily accessible for examination and repair, and when repairs of a major nature are in progress this work should in no way interfere with the ease of operation of the plant in service.

For some years the majority of boiler plants have been designed for superimposed assembly; that is to say, the economizer, if incorporated, was erected above the boiler, the air heater was erected above the economizer, and the fan equipment and chimneys were arranged above these three items, and, therefore, generally on the roof. Such a lay-out is inaccessible for both operation and repair, and necessitates a multitude of gangways, platforms, and ladders. The final result is that the lower—and usually the operating floor—levels are robbed of almost all natural light.

Modern practice is confined almost entirely to two methods of arranging the boiler plant in relation to the

turbine room. In the one case the boiler units are housed in one or more buildings having one gable at right angles to and forming part of the turbine-room wall, and in the other case the boiler plant is housed in a building arranged parallel to and adjoining the turbine-room wall. The choice of either design is dependent, to some extent, on the number and size of the turbine units and their arrangement in the turbine room. Further, consideration has to be given to the cost of buildings for either scheme, to the lengths of main and auxiliary steam ranges required, and to the bunker conveyor arrangements. With either scheme the boiler units can be arranged for operation from a central aisle or by arranging them back-to-back from two wing aisles. The central operating aisle has a big advantage in that one operator can comfortably handle the maximum number of units, and the principal controls and instruments of these units can all be within his range of vision. It would appear, however, that this advantage will not hold in the near future. Boiler units are now of such a size that there is a growing demand on the part of operatives and their societies that the responsibility should be limited to one boiler unit per operator.

The central operating aisle lay-out for boiler plants at right angles to the turbine room provides a maximum of natural light from the end gable. As a rule this arrangement necessitates more than one boiler house for the complete station. This means that the boiler houses are short in length, and the operating floor can be naturally lit even as far as the boiler units next to the turbine-room wall. Further, both walls can carry a maximum of glazing, giving ample light at the rear of and between the units.

The central aisle of a parallel-arranged boiler house in a large station is, in comparison, dark around the centre, and at all times the rear of the units next to the turbine room requires artificial lighting.

With the central operating aisle the bunker arrangement can be such that the central roof can be sloped on either side and fully glazed, thus providing for natural light on the higher sections of plant and also permitting additional lighting to reach the operating floor through the space between the bunker wall and the tops of the boiler units.

The various components forming the boiler unit should be so arranged that routine operation can be effected from as few levels as possible. The economizer and air heater of each unit should be arranged at the rear of the unit and not superimposed as has hitherto been general. The section of gas pass forming the economizer outlet and air-heater entry should be so designed as to form a dust arrestor. With the boiler unit assembly suggested this means that the bulk of the dust can be extracted at this point and discharged to the ash-disposal plant in the basement. Further, such an arrangement provides a saving in building height, with a saving in capital cost of bunker conveyors and cost of operation. Space should not be stinted between and at the rear of boiler units. Any plant or controls situated in cramped or inadequately lit locations will be neglectfully operated and will not receive its due measure of attention to cleanliness.

The boiler fans, both for forced and induced draught, should be located on the main operating level. This can be easily effected with stoker-equipped units, and is also possible, with some thought, in the case of pulverized-fuel-fired units. This location for the fans ensures that they will receive the attention of which they are deprived when arranged in places which are inaccessible, dark, or dirty. Further, this attention can be given by the boiler operator, who is principally interested in their behaviour. With this lay-out it may mean that the forced-draught fan will be required to handle hot air, since it may have to be on the air exit end of the air heater. This, however, is not a serious point and is more than offset by the other advantages gained. Again, with the fan equipment in this location, repairs, routine maintenance, and plant examination are all more easily effected, particularly such items as runner overhauls and heavy electrical work.

The vertical space between and at the rear of the units should be as free from obstructions as possible, and platforms and galleries in these places should be kept to the bare minimum.

The fronts of the plant facing the operating aisle should also be free from all galleries or platforms, and should present nothing but the boiler casing panelling. The size of present-day individual boiler units is making the question of observation of boiler water-level a costly proposition. The height from operating floor to the boiler-drum centre line is in many cases so great that no attempt is made to place the water gauges in the sight of the men on the operating floor. Instead the plant is laid out with facilities for the accommodation of water tenders. This arrangement on a large plant can increase the operating costs by as much as £3 000 per annum. It is suggested that where the height is excessive for direct observation the problem can be solved by bringing forward one of the gauges of each unit and equipping this gauge with proper illumination and a periscope, with the necessary lenses, mirrors, or ground-glass screen. This need not be prominent nor unsightly, since each can be arranged in the building column nearest its particular boiler unit. There are various types of instruments available for the distant indication of boiler water-level, but they do not fully solve the problem. The author does not question either their reliability or accuracy.

As previously stated, galleries and platforms should be kept to a minimum. Wherever they are required they should be constructed of one of the types made up from steel strip on edge, and, consistent with strength, the type chosen should pass the maximum amount of light. Certain designs of boiler unit require periodic work on header caps, and with this design it is customary to provide access galleries for this purpose. It is suggested, however, that these galleries are unnecessary. The casing doors can be hinged and so designed that when lowered to the horizontal they form a platform from which the work can be carried out. The design of the hinge and door-sealing requires care, so that when closed the doors are both gas- and dust-tight. This remark applies generally to all casing doors and the ordinary panelling. For extensive boiler repair work, such as at annual overhauls when easy access to the whole front and rear of this design of boiler is required,

scaffolding of the sectional tubular type is very useful. It takes up a minimum of room, is strong, safe, and easily and quickly erected or dismantled, and it is not unsightly. Its use is also an advantage for reconstruction work in the modern large combustion chamber.

The main operating controls for each unit should be grouped and arranged near the front of the unit. The principal feed-water control valves should be provided with extended spindles and carried to this point so that they are readily available to correct any erratic behaviour of the automatic regulators.

The main damper controls should also be grouped here, and from this position all the instruments on the control panel should be visible. The damper controls should be of the signal lever or wheel, worm, and quadrant type, and should be definite and accurate in action. The wires or chains connecting dampers to their controls should not be visible.

The chimneys of the plant should not be carried on the building steelwork, but should be erected outside the building and carried on supports forming part of the main building foundations.

ACKNOWLEDGMENTS.

In conclusion the author desires to record his thanks to the following undertakings and gentlemen for their assistance in the preparation of this paper: The Lancashire Electric Power Co., Ltd., through Mr. M. H. Adams; the City of Birmingham Electricity Supply Department, through Mr. F. Forrest, Member; the Detroit Edison Co., through the President of the Company, Mr. Alexander Dow; Messrs. Merz and McLellan, consulting engineers, through Mr. E. C. Ward; and the County of London Electric Supply Co. Ltd., through Mr. W. J. H. Wood, Member, and Mr. J. A. Vice, Associate Member.

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Mr. W. M. Selvey: Tables 1, 2, 5, and 6 show that numerically the figures of merit for steam raising and steam utilization are now equal, and in my opinion this is due to the advent of pulverized fuel. Tables A and B, which give the results of four selected tests made under very strict conditions, show that not only has improvement been made in the very large boilers, but small boilers have equally benefited. Further progress will be along the lines of increased economy in the use of material. For instance, English turbine makers are putting into service sets with a maximum continuous rating of 30 000 kW at 3 000 r.p.m.: there is equal scope for increasing the rating of a given amount of boiler material. The notable examples of the Wood boiler and the Johnson boiler show that designers are now concentrating upon the furnace-type boiler, practically without refractories. Improvement of the steam cycle by the use of higher pressures and temperatures is increasing the available energy per pound of working fluid, and thus enabling us to obtain more service from a given amount of material. Progress in the size of the plant, while not directly increasing the output of the active material, greatly decreases the relative cost of the inactive associated structure. In the struggle to attain higher efficiencies, the use of hot air in stokers has in many cases been pushed beyond the practical limit. Coal of the coking or semi-coking varieties has a softening temperature, and the first products of distillation have an ignition temperature. If the latter is near to or above the former it becomes essential to rush the coal through its ignition stage in order to prevent the formation of a mass of coke; this is a difficult thing to do, and necessitates the adoption of special measures. The temperature of the hot air may be below the softening and ignition temperatures, but the temperature of a grate which is surface-cooled only by the hot air may be well above them. When in contact with the hot grate, the dust coal in the mixture to be burnt may rapidly reach the softening point, and not reach the ignition point. It then starts to agglomerate, the air flow is checked, and finally large masses of coke form which cannot be burnt at coal-burning rates. In these circumstances, grate temperatures must be reduced and the coal thoroughly wetted.

Mr. W. N. C. Clinch: In regard to the suggestion (page 544) of having 4 boilers per turbine unit with 3 normally in commission, I know of one English power station where only 5 boilers are provided for a 2-turbine plant, so that the practice which the author advocates is already being adopted in this country. The figures given for the operating efficiency of the station with which the author is associated compare favourably

TABLE A.

	1	2	3	4
Type of boiler	Cross-type marine	Straight-tube horizontal-header	4-drum straight-tube, with header	5-drum bent-tube
Type of stoker	Twin chain-grate, compartmented	Multiple-retort	Twin travelling-grate, enclosed-front, compartmented	Twin travelling-grate, open-front, compartmented
Date of test	March 1929	June 1930	April 1931	July 1931
Boiler heating-surface, sq. ft.	9 618	12 000	9 952	16 000
Superheater heating-surface, sq. ft.	4 075	2 880	2 870	2 940
Economizer heating-surface, sq. ft.	6 048	5 443	1 862	5 610
Total heating surface, sq. ft.	19 741	20 323	14 684	24 550
Air-heater heating surface, sq. ft.	11 760	14 040	2 160	9 230
Type of fuel	washed slack	Northumberland dry slack	1-inch screened slack	Yorkshire dry slack
Gross calorific value of fuel as fired, B.Th.U. per lb.	11 416	10 970	9 210	10 525
Net calorific value* of fuel, B.Th.U. per lb.	10 858	10 463	8 674	10 012
Normal output of boiler, lb. per hour (actual)	62 000	82 000	42 000	81 700
Pressure, lb. per sq. in. (gauge)	275	200	250	383
Total temperature, ° F.	660	588	605	731
CO_2 at induced-draught fan, per cent	11·05	11·30	9·25	10·62
Flue-gas temperature at induced-draught fan, ° F.	230	269	333	277
Boiler efficiency (calculated on gross calorific value), per cent	83·6	84·8	83·4	84·7
Boiler efficiency (calculated on net calorific value), per cent	87·9	88·9	88·6	89·1
Ash-pit loss, per cent	1·8	4·0	1·0	1·0

* Based on Institution of Civil Engineers' "Report on Heat Engine Trials."

TABLE B.

	1	2	3	4
HEAT ACCOUNT ON GROSS CALORIFIC VALUE				
Gross calorific value as fired, B.Th.U. per lb.	11 416	10 970	9 210	10 525
Heat to steam, per cent	83·6	84·8	83·4	84·7
Heat loss to flue gases, per cent	9·5	9·9	15·0	11·2
Ash-pit loss (heat to ash and unburnt fuel), per cent	1·7	4·0	1·0	1·0
Heat to radiation and unmeasured losses to balance, per cent	4·9	1·3	0·6	3·1
Heat to auxiliaries,† per cent	1·7	2·3	1·8	1·9
Net boiler efficiency with auxiliaries, per cent	81·9	82·5	81·6	82·8
HEAT ACCOUNT ON NET CALORIFIC VALUE				
Net calorific value, B.Th.U. per lb.	10 858	10 463	8 674	10 012
Heat to steam, per cent	87·9	88·9	88·6	89·1
Heat loss to flue gases, per cent	4·9	5·0	9·7	6·0
Ash-pit loss (heat to ash and unburnt fuel), per cent	1·8	4·2	1·0	1·0
Heat to radiation and unmeasured losses to balance, per cent	5·4	1·9	0·7	3·9
Heat to auxiliaries,† per cent	1·8	2·4	1·9	2·0
Net boiler efficiency with auxiliaries, per cent	86·1	86·5	86·7	87·1

† Based on Institution of Civil Engineers' "Report on Heat Engine Trials" (20 000 B.Th.U. per kWh = 17 per cent efficiency).

with those shown for American power stations, and this would indicate that the trend of development is already on the lines which he advocates. I should like to refer to the peculiar expression he uses for plant efficiency. Surely in operating a boiler plant we are more interested in minimizing the variable losses which result from bad operation than in removing the fixed losses due to design. I therefore cannot see any particular value in the figure which he puts forward. Has it been at all widely adopted? The boiler lay-out shown in Fig. 3 is not as simple as it looks. Although I agree that pulverized fuel is probably the most effective means of oxidizing coal to liberate heat, to employ all sorts of auxiliary appliances in order to make the coal suitable for pulverized-fuel firing is to defeat the end in view. Unless the pulverized-fuel equipment can be installed in a space approximately equal to that occupied by a chain-grate stoker the capital costs will be unduly increased. What is the advantage of the central system illustrated in Fig. 3? The fact that no outages have occurred in connection with the plant is not due to any merit of pulverized fuel but merely to the group system, which enabled use to be made of other plant in substitution for the defective units. I therefore consider that where pulverized fuel has to be employed the unit system should be adopted. The disadvantage of the central system is that by storing the pulverized fuel in a compressed state in bins much of the value of the initial pulverizing is lost. The unit system is often stated to be unreliable, but I think we can pay too much attention to such " reliability." Provided the plant is so designed that every part has the same liability to breakdown, the question of specific reliability is not very important. For instance, a breakdown of the draught fan will probably cause just as complete a shutdown as the failure of the pulverizing equipment. The present practice of bringing the fuel as near as possible to the combustion chamber gives every facility for duplicating the pulverizing equipment, and thus the reliability can be made equal to that of a central system. As regards combustion chamber design, I am convinced that the use of some refractory is of advantage in that it ensures early combustion. In connection with soot-blowing, I do not agree with the suggestion that by means of a suitably designed low-gas-velocity boiler plant one could remove all the grit liable to give rise to trouble. During a period of soot-blowing a perfectly clean chimney is an impossibility, whatever the size of the duct, and large ducts are not easy to arrange if one requires the maximum output from a given ground space. The remarks under the heading " Arrangement of Boiler Plant " illustrate the value of co-operation between the manufacturer and the user of the plant. In my opinion powdered fuel will be employed in the future for large units, and I am convinced that it will not be long before the difficulty of grit collection is overcome. In the case of a power station situated near the sea there should be ample scope for getting rid of objectionable materials.

Mr. H. P. Gaze: The author expresses a preference for what I may term the ground-floor or " bungalow " type of boiler of which the Kearsley station is an example, and for stations situated in rural areas where land is cheap this type may be the best to adopt; but in urban or suburban districts such a lay-out is very costly. I think that in the large boiler designs of the future the whole of the ground-floor space will be taken up by the boiler and stoker. The author's ideal boiler rating of 5·5 lb. per sq. ft. of heating surface is a very low figure, and if it were adopted (which is very unlikely) the remarks I have made about the space occupied by the bungalow boiler would be emphasized. I should like to refer to a development in connection with high-rated boilers which has recently been adopted at the Willesden station of the London Power Co. We have recently installed, in a space previously occupied by three standard boilers each of 50 000 lb. per hour normal rating, three boilers with a normal evaporation of 90 000 lb. per hour and a maximum continuous rating of 120 000 lb. per hour, i.e. nearly double the previous rating. These boilers, which have been working for five or six months, are all of the standard sectional type, equipped with water walls and the usual air-heaters and economizers. The evaporation at normal duty is 11 lb. per sq. ft. of heating surface, and the maximum continuous rating easily obtained is 14 lb. per sq. ft. The combustion chambers are abnormally high for this type of boiler, measuring 18 ft. 6 in. from the grate to the bottom of the tubes, and the efficiency curve is particularly flat, which does not fit in with what the author says on this point. The efficiencies obtained on careful long-period trials vary from 86 to 88 per cent at 80 to 120 per cent of normal duty. The statement on page 557 that the control of this type of boiler is critical and difficult is in no way confirmed by our experience. On the contrary, the control of combustion has been particularly easy. A high percentage of CO_2 is maintained without difficulty and with an almost complete absence of smoke. The high gas-velocity on this boiler has the effect of giving particularly clean surfaces; it seems to have almost the effect of soot blowing. The London Power Co. have four boilers in another station which have been equipped with high-duty travelling-grate stokers: whereas the boilers were formerly rated at 60 000 lb. per hour, they are now easily attaining between 90 000 and 100 000 lb. per hour. Each of the travelling-grate stokers is set within square walls in the boiler furnace, without an arch. They are working with rather highly boosted secondary air, and the combustion is distinctly turbulent. A CO_2 content of 15 per cent is maintained all day without the slightest difficulty, and 16 per cent has been reached, without any trace of CO. Further, the boilers are abnormally smokeless. In accordance with the author's suggestion on page 544, I should like to refer to the retort-type stokers in the stations of the London Power Co. Those originally installed in the Deptford station in 1929 were for three comparatively small boilers of 64 000 lb. per hour normal rating; they were the first retort stokers of this type employed in this country and, I think, the second on this side of the Atlantic. The stokers were originally designed for the low-volatile coals of America, and it was found difficult to burn the high-volatile British coals upon them. As now modified, however, they are satisfactorily dealing with British coal. Two stokers of a further modified design have been working satisfactorily for about

4 months on boilers of 160 000 lb. per hour normal rating, and they have been run for long periods at the maximum continuous rating—200 000 lb. per hour. All these boilers are equipped with water walls, in accordance with standard practice. Owing to the modifications found necessary to the former stokers, the maintenance cost has been comparatively high, viz. 3½d. per ton of coal burnt; experience indicates, however, that this figure will be materially reduced. The figure for chain-grate repairs obtained from two stations which are worked continuously is of the order of 1½d. to 2d. per ton of coal burnt. The experience obtained with these retort stokers shows them to be a good alternative to pulverized fuel. They provide a clear chimney, and the fact that the ash is rejected cold means that there is no loss of sensible heat. There is much less atmospheric pollution than with the pulverized-fuel boiler. Proper gas washing will not only assist the powdered-fuel type of boiler, but will also be an advantage to the stoker type when soot blowing is in progress. A satisfactory full-scale system of gas washing has been installed on one boiler at the Grove Road station which has been working for over 12 months. With this system a boiler left uncleaned for 2 or 3 weeks can be effectively cleaned with the soot-blowing apparatus in one operation, without the slightest emission of grit or dust from the chimney. I should like to stress the point made by the author as to the lack of information on the results of power station operation in this country, a position in marked contrast to that in America. I hope that when the Central Electricity Board is responsible for the running of the selected stations, it may feel able, with the co-operation of the owners, to publish a great deal of useful information on this subject.

Mr. W. E. Highfield: The problems which the Union d'Électricité has had to face are similar to the problems that face the supply authorities in London and the larger provincial cities in this country, and Mr. Rauber has supplied as a contribution to this discussion the following information relating to the latest policy and experience of the company at Vitry South and Gennevilliers. Gennevilliers was built some 10 years ago as a base-load station. Later, other stations were built (notably at Vitry) and Gennevilliers was extended. A further step in policy was taken some three years ago, when it was decided to extend Vitry and make it the main base-load station, and simultaneously to reconstruct the Gennevilliers station. It was decided to make a difference between the design of the boiler house at the new Vitry station, termed "Vitry South," and that of the reconstructed boiler-house at Gennevilliers. Vitry South, as the main base-load station, had to be designed for the highest possible efficiency, and therefore its cost could be relatively high. The boilers at Vitry South were therefore designed for powdered fuel and were arranged with economizers and air heaters to give the maximum economy. Gennevilliers, on the other hand, had to be prepared to deal with peak loads due to fluctuations and breakdowns that might occur elsewhere. The boiler-house plant had in consequence to be efficient, but its efficiency had to be definitely related to cost. Careful estimates showed that considerations of cost made it impossible to adopt pulverized fuel. The decision finally taken was to install a completely new type of single-pass boiler so as to reduce the running losses to a minimum; and to design it so that it could easily be erected on the foundations of the boilers to be replaced. It was also decided to design a special type of furnace, partly water-cooled and partly refractory, based on the experience gained at Gennevilliers. The new boilers at Gennevilliers were made the same size as those projected for Vitry South, but different pressures and temperatures were adopted. At Vitry South the pressure is 500 lb. per sq. in. (gauge) at 840° F., and at Gennevilliers it is 425 lb. per sq. in. (gauge) at 750° F. The output in both cases is 240 000 lb. per hour normal and 300 000 lb. per hour emergency rating. The original Gennevilliers boilers were built for 350 lb. per sq. in. at 700° F., but it has been found possible to modify the turbines by providing a high-pressure cylinder and thus rendering them more efficient; this change to the turbines forms part of the reconstruction programme. The design of the new boilers at Gennevilliers (see Fig. A) is due to Mr. Rauber and his colleague Mr. Luquet, of the Union d'Électricité. The first rows of tubes are smooth, but all the others have gills electrically welded to them. The superheater tubes are also gilled throughout. There are 44 sections of boiler tubes, each consisting of 17 tubes. Five tubes only are smooth, these being 83/94 mm in diameter. The other 12 tubes are 74/82 mm in diameter and are fitted with gills ranging from 140 × 140 mm to 170 × 170 mm, all of them being 5 mm thick. The surface area of each gilled tube is 1·085 m^2, and the surface area of the gills is 2·94 m^2. The tubes are set at an angle of 45° so as to maintain a predetermined velocity of the gases despite their cooling. The superheaters are interposed and suspended from the seventh row of tubes. Each superheater comprises 86 tubes, 34/42 mm in diameter, with four bends, fitted throughout with 82 × 82-mm gills. The surface area of the complete nest of superheater tubes is 240 m^2, and of the gills 524 m^2. Spaces are allowed to give access to the nest of tubes for cleaning and repair. The horizontal space requirements of the boilers are:—Width between walls, 8·68 m, length of first tube, 8·82 m. The combustion chamber comprises refractory walls made up of independent horizontal steps partly protected by water screens, spaced and placed in contact with the walls. Screens of this nature are placed on the four vertical faces of the chamber. The water circulation in the screens is connected into the boiler circuit. Two of the first installation of four boilers are fitted with Taylor stokers, each of which has 16 troughs with 57 nozzles. The side walls are cooled by inclined water-tube screens, certain of which are protected by cast-iron blocks. The other two boilers are fitted with stokers designed by M. Ratel, of the Union d'Électricité. These stokers differ from the Taylor stokers in that the inclination is much less and the coal enters by means of pushers placed on the bottom of the troughs, which are closed underneath. The side walls are protected by compressed-air headers, the air being supplied by a special fan. Air is supplied to each furnace by two blowers capable of dealing with 135 000 m^3 of air per hour at 220 mm pressure. The motors are of 140 h.p. Each boiler is fitted with a steel-tube economizer.

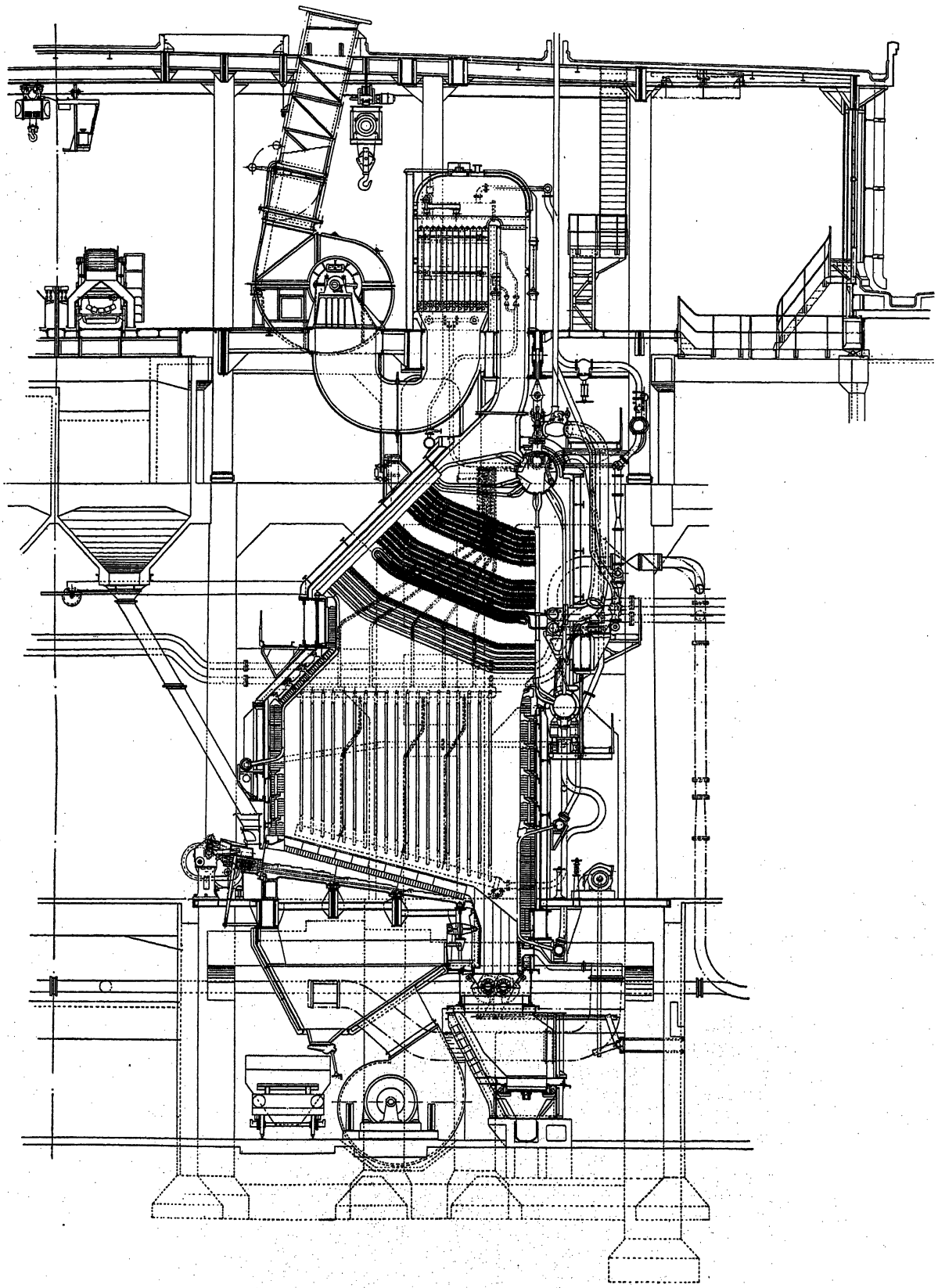


FIG. A.

The tubes are narrow and—on three boilers—smooth, the area being 1 800 m^2. As an experiment, the fourth economizer has been fitted with gills. The area of the gilled-tube economizer is 2 700 m^2, but in spite of the increased area it takes up less space than those fitted with smooth tubes. On account of space limitations, no air heater has been fitted. The feed water is obtained at 80 to 85° C. from two stage heaters supplied from the turbines. The exhaust gases from the economizer pass through two parallel motor-driven fans, into an unlined steel chimney. The ashes are removed by hydraulic conduits sealing the ash pit. Each boiler is fitted with a complete set of measuring and recording instruments. The two boilers fitted with Ratel stokers have been in service since November 1931. The results obtained so far are very gratifying, and justify the policy adopted by the Union d'Électricité. They may be summarized as follows.

(*a*) Normal loads up to 265 000 and 30-minute loads up to 320 000 lb. per hour have been easily carried.

(*b*) With a CO_2 content of 13 to 14 per cent the temperatures are:—

	200 000 lb. per hour °F.	320 000 lb. per hour °F.
Leaving boiler	280	340
Leaving economizer	140	155

(*c*) The partial vacua with 13 to 14 per cent CO_2 content are:—

	20 000 lb. per hour mm	320 000 lb. per hour mm
Leaving boiler	3	6
Leaving economizer	25	55

(*d*) Using natural draught the boilers have carried up to 265 000 lb. per hour with a CO_2 content of over 14 per cent. The chimney is 62 m above the plane of the grate.

(*e*) With a load of 320 000 lb. per hour, the power in kW absorbed by the auxiliaries is:—

	kW
Blowers	115
Grate	23
Clinker crushers	5
Induced-draught fans	52
Total	195

This corresponds to 0·7 per cent of the power supplied by the boiler.

(*f*) The flexibility of the boiler is surprising. Under conditions of normal operation the boiler was connected to the line 33 minutes from the time of lighting the fires, and within 60 minutes it was carrying over 200 000 lb. per hour.

(*g*) At normal rating the overall efficiency is just over 85 per cent. Naturally one of the most interesting points investigated was the behaviour of the gilled tubes with regard to sooting. One set of soot blowers is placed in front of the superheater and one set between the eleventh and twelfth rows of tubes, where there is an inspection space. No. 3 boiler was run under service conditions for 708 hours and then opened up for inspection. No soot blowing had been done on the boiler tubes. The first row of smooth tubes were found to have irregular masses of agglomerated dust on the under-side; this was several centimetres thick in places, but was readily detachable. The other smooth tubes were only slightly dirty. The gills of the sixth row of tubes, in front of the superheater, were covered irregularly with a layer of fine white dust 0·1 to 0·2 mm thick. The fins of the superheater tubes were somewhat dirtier; in some places the dust layer was 1 mm thick. On the boiler tubes behind the superheater the layer of soot decreased regularly, being 0·1 to 0·2 mm thick at the commencement. In the last rows there was no appreciable deposit. Throughout the nest of tubes there were, of course, accumulations of dust which formed cone-shaped heaps on the tops of the tubes. As a result of the experience already gained it is considered that soot blowing will be confined to the superheater tubes, and that the boiler itself will only require cleaning when it is opened up for routine inspection a few times per year. It would appear that the Union d'Électricité have achieved a technical and commercial success by producing a high-efficiency boiler house with a low capital cost and low running charges. The reconstruction of existing stations on more economical lines may prove to be an important factor in the future of electricity supply.

Mr. A. L. Lunn: I should like to refer to the question of the maximum temperature of the preheated air, which the author states (page 544) should not exceed 350° F. Mechanical troubles necessitating extensive repairs and replacements to travelling-grate stokers are frequently experienced where temperatures of 270° to 300° F. are employed. On the other hand, if the temperature is kept down to 250° F. the same type of stoker, using the same class of fuel, will give very good service. I have formed the opinion, therefore, that the critical stage for reliable operation is between 250° and 270° F. As regards Table 3, I think that the figure of 2 per cent for " heat lost in radiation and unaccounted for " is rather low for the type of boiler referred to. With regard to the induced-draught fans and grit-arrestor equipment (page 552), the life of the fan runners is stated to be between 6 000 and 7 000 hours. On a particular installation it has been found necessary after only 3 000 hours to replace, or extensively repair, the impeller and fan casings. Recently the life has been increased, however, by making the blades of a nickel-steel alloy, constructing the fan casing in segmental sections, and inserting wearing-plates. It is obviously best to install the grit-arresting equipment on the suction side of the fan. I am familiar with several equipments fitted in this way which have been operating successfully for several months without showing any signs of wear. The fitting of hydraulic couplings to the induced-draught fan, apart from saving auxiliary power, has a marked effect in preventing wear of the fan equipment. Owing to the fact that fan makers allow for a large overload capacity the velocity is usually higher than necessary, and by fitting these couplings one can considerably reduce the volume of grit-laden gases. On a large number of installations a certain amount of damper control is practised at the economizer or air-heater outlet, resulting in unduly high velocities between the damper and grit arrestor. As a result the

grit arrestor suffers a loss of efficiency, which leads to grit emission to the atmosphere and greater wear on the equipment. Turning to the question of "bird-nesting" (page 557), I agree with the author as to the effect of high gas velocities. It is necessary to clean certain boilers at the end of 300 steaming hours, whereas the same type and capacity of boilers using the same class of fuel, but operating with a much lower gas velocity, will steam for 1 000 hours before it is necessary to lay them off for cleaning. I agree with the author's view that for soot blowing air has an advantage over steam. Soot-blowing elements which employ superheated steam and are therefore subjected to high temperatures, have a tendency to "creep" and distort from their settings. This effect renders them not only useless but positively detrimental, in that the steam jets impinge on the generator tubes and give rise to a considerable amount of damage. The maintenance cost of soot blowers is very high, and the fact that in many cases they are only operated once every 24 hours prevents them from being effective. It is therefore doubtful whether the existence of certain types of soot-blower equipment is economically justified. Turning to the section dealing with superheaters (page 559), I look forward to a great advance in this direction before very long. An outstanding improvement in both material and design is necessary. The existing high maintenance cost and outage hours, to which the author's own experience can testify, demand serious attention. The short life of the hangers, supports, etc., calls for a design embodying larger numbers of shorter tube lengths, which would need little supporting. The author suggests that separate and definite control of the heat supply to the superheater is needed, but this appears to have many difficulties as any form of damper or movable baffle would undoubtedly give trouble when subjected to high temperatures. Since the advent of pulverized-fuel firing considerable improvements have been made in travelling-grate stokers, but manufacturers are still slow to realize that better material and finish are necessary. Problems such as effective sealing do not receive the attention they should. I regret that the author gives such scanty details of the effect of high temperature on such parts as steam-range joints, bolts, superheater tubes, safety valves, and safety-valve springs. It would be interesting to have his views on the amount of concentration to be carried in the boiler water of modern boiler plant, bearing in mind the loss due to blowing-down, and also his opinion on the question of caustic embrittlement. With regard to Mr. Gaze's remarks, I am of the opinion that for large boilers the retort-type stoker will be extensively used in this country in the future.

Mr. W. S. Burge: The author states that boiler pressures and temperatures are becoming standardized in the United States, and that there seems to be a definite choice between pressures of 500 to 600 lb. per sq. in. and 1 000 to 1 400 lb. per sq. in. Some two or three years ago I thought that we in this country were also approaching finality in regard to steam conditions, but since that time there has been a large amount of development in the way of blade sheathing on the low-pressure blades of turbines, and considerable advances have been made in the design of superheater tubes. In consequence we are now able to run our turbines with a higher moisture content through the last rows of blades, and also to operate our boiler superheaters satisfactorily at still higher steam pressures and total temperatures. The net result of these developments has been to increase the range of practical steam conditions beyond which steam reheating becomes necessary. In these remarks I refer more to the physical possibilities of operation than to economic advantages, and I am still of the opinion that from an economic point of view there may be a much better case for standardizing steam conditions than would appear at first sight. The question of pulverized-fuel versus stoker firing depends much more on boiler rating than on boiler efficiency. In an overall boiler efficiency two entirely different factors are involved, namely heat release or combustion, and heat reception or the passage of released heat into water for the purpose of raising steam. The method of firing, whether by pulverized fuel or by stokers, can at the best only affect the heat-release component, and, of the two, combustion efficiency leaves by far the smaller margin for improvement. With regard to the question of evaporative rating, there is no doubt that pulverized-fuel firing eliminates the output limitation of coal per square foot of grate area that applies to stoker firing. A few years ago this limitation was rather definite with our British coking coals, but the recent rapid developments in the direction of retort-type stokers will, I think, greatly widen our previous limitations. It is probable that even at the present time evaporation outputs up to 300 000 lb. per hour can be satisfactorily dealt with by retort-type stokers, and there is reason to expect that in the next few years this figure will be increased to 500 000 lb. per hour. I agree with the author that the most difficult question of the moment is that of superheating under conditions of high pressure and temperature. I have for some time felt that the niceties of fuel regulation made possible by the use of pulverized fuel could be applied for superheating purposes only by means of separate superheating boilers using pulverized fuel. In this connection I am of the opinion that automatic combustion control would be particularly valuable, and I have been surprised at the extreme sensitiveness and reliability of the combustion control employed in the United States. If automatic combustion control were developed for sensitive regulation in regard to superheating on separate superheating boilers, the main evaporative boilers would be relieved of the design embarrassment of superheater tubes. Such a development could probably only be justified for boilers of very large output.

Mr. J. W. J. Townley: Although the author remarks that thermal-efficiency statistics can have only an academic interest unless they are accompanied by an analytical statement of the cost involved, he does not supply such a statement. It is often found that it does not pay to modernize an old boiler plant because the capital charges associated with high thermal efficiency are not balanced by savings achieved consequent upon the reduced fuel consumption. The cost of attaining very high thermal efficiencies is in many cases unjustifiable on commercial grounds, and there can be little

doubt that the conservative development of the last few years in this country has been entirely justified. Actual figures of the performance of recently designed plants are badly needed to enable us to determine the upper limits of thermal efficiency commercially desirable. I am convinced that the retort-type stoker has great possibilities. The American design first used in this country was too short for our fuels, had too steep a slope (this caused " avalanching "), and gave unsatisfactory results from the point of view of smoke. I was interested to hear Mr. Gaze say that the smoke trouble had been overcome, for if this is so the retort-type stoker will be a serious competitor to pulverized fuel. The ease with which the retort-type stoker can be designed for fitting to a very wide boiler makes it suitable for the 300 000-lb. per hour type mentioned by the author. One advantage of the retort-type stoker is its remarkable freedom from " outages " in comparison with chain-grate stokers. The experience at the Battersea station with retort-type stokers will be awaited with great interest by all power station engineers.

Mr. W. Hamilton Martin (*communicated*): I should like to refer to the author's statement that the superheater tends to become the most vulnerable section of the boiler unit. A large amount of research has been done in the last few years with a view to obtaining materials capable of withstanding continuously temperatures from 900 to 1 100° F., without showing signs of scaling and oxidation, while offering good cold working and welding properties and proving economical to install and use. Such materials have now become available,* and they can be drawn to any required length. One of these is a molybdenum alloy which shows great strength and toughness at higher temperatures, and has good " creep " properties. It can be used for tubes whose outer walls have to withstand about 930° F. continuously. The other is a relatively low alloyed steel of a chromium-aluminium basis, and is obtainable in four different grades. These alloys are non-scaling, and as they have a high yield point when hot appreciable reductions in wall thickness with a higher factor of safety become possible; this feature also means a saving in weight, and hence in cost. Tubes made of these materials can withstand very high operating temperatures, e.g. from 800° C. (1 470° F.) to 1 200° C. (2 200° F.). They show exceptionally good working features, and are, it is believed, an advance on everything else of their kind. Their exceptional resistance to gases with high sulphur content is mainly due to the fact that they contain no nickel, a metal which is very sensitive to sulphur absorption. The life of hangers, supports, slings, and possibly of the security studs described, can be greatly increased by the use of these alloys. The presence of nickel in security studs may have contributed to their early failure. The new alloys may be used for stoker or burner and furnace parts, and they may also overcome the present difficulties of blistering in vertical-tube walls, where less refractory materials are now being fitted in the combustion spaces. They will probably also be suitable for the manufacture of draught, air-heater, soot-blowing, exhausting, dedusting, sulphur-removal, and ash-removal equipment. No reference is made in the paper to boiler drums, and I should like to state that where their cost is an appreciable item great use is now being made abroad of water-gas-welded drums. During the last 8 years more than 1 000 have been installed all over the world; 70 per cent operate at over 500 lb. per sq. in. pressure, and some of them at 930 lb. per sq. in. None of them has ever given cause for complaint. They offer a great saving in cost as compared with forged drums, while their method of manufacture, excess-pressure test, and annealing, ensure a stress-free and reliable article. It is to be hoped that before long this method of construction may find more general adoption in this country. Although several of our insurance companies have already insured welded drums, the majority are waiting for the Board of Trade to approve water-gas-welding of boiler shells, as has now been done in practically every other country for very high working pressures, or if weight has to be saved, as may be the case in marine or mobile plant, the wall thickness of such drums may become excessive, where only soft steels can be used for welding. To meet such cases a continuous rolling process has just been perfected on the Continent by which seamless rolled large boiler drums can be produced. This method takes the place of the laborious and costly forging down and machining of a heavy ingot into a drum, and offers obvious advantages over the latter. If, moreover, the special steels now available for that purpose are employed, further appreciable savings in weight become possible, while these materials at the same time offer an increased factor of safety.

Mr. A. M. Selvey (*U.S.A.; communicated*): As it is the purpose of the paper to cover a wide field in boiler practice, the following short description of a fairly radical change from the standard design of boiler unit will not be out of place. The steam-generating unit adopted by the Detroit Edison Co. for their new Delray (No. 3) power house is of the single-ended Stirling type. This type of boiler was decided upon because of the advantages to be obtained by having only one firing aisle, one row of bunkers, and a simple arrangement of coal conveyors. The economizer and preheater are placed behind the boiler, thus reducing the building height and spreading the weight to be carried by the foundations. The concentrated weight of the bunkers over the firing aisle is supported by the caisson-to-rock type of foundation, which is used for the entire power house. When the construction of the plant was first contemplated, a comparison of the efficiencies and costs of stoker firing and firing by means of the unit system of pulverized fuel showed these to be practically equal. In order to take advantage of any future developments in the economy of fuel burning, the boiler was so designed that it could be operated, with few changes, by either method of firing. The influencing factors in the final adoption of stoker rather than pulverized-fuel firing were the objection—due to the location of the plant in the city—to the emission of fly-ash, even with precipitators in operation, and the difficulty of disposing of pulverized-fuel refuse. Single-ended firing necessitated a stoker of 57 tuyères long and 15 retorts wide, having a projected grate area of 611 sq. ft. Owing to the large size of the grate, some means of metered air control

* See *Transactions of the Institution of Marine Engineers*, 1931, vol. 43, p. 581; also my remarks on Mr. Jackson's paper in vol. 44.

had to be provided to reduce the formation of light and heavy spots in the fire. An automatic air control consisting of 56 separate units in 4 rows was installed under the tuyère stacks. The unit is a welded sheet-steel box containing an orifice and a control damper, both being of the cylindrical type. The orifice opening is automatically adjusted according to the wind-box pressure. The control damper is operated by the pressure differential across the orifice and is in a state of balance under a normal fuel bed. A local change in the thickness of the fuel bed, causing a variation in the volume of air passing through the orifice, upsets the balance of the control damper, which operates to oppose the change until a new position of balance is attained. The control damper has been found to effect a change of from 10 to 15 per cent in the volume of the air supply. Owing to the sensitivity of the apparatus to changes, this amount has proved sufficient to rectify any variation in the fuel bed experienced in the normal operation of the stoker. The original stoker had 6 pushers, each with an independent adjustment. Since the adoption of 4 zones of air control, a 4-pusher arrangement has proved to be more effective. During recent tests on a boiler fired with a 4-pusher stoker, a CO_2 figure as high as 16·5 per cent was obtained at the boiler outlet. High CO_2 content, better packing of the fuel bed, and greater control of the fuel for combustion—due to the stoker having the same number of pushers as air-control zones—resulted in a saving of electric power to auxiliaries as high as 38 per cent of that required for a boiler fired with a 6-pusher stoker. The top pusher being about 8 ft. above the operating floor, a platform had to be provided to give access to the stoker-gear boxes. The necessary instruments for the boiler control are mounted on the operating board, which is placed below the platform in front of the stoker. The boiler unit is designed for an evaporation of 340 000 lb. per hour, but under test conditions 410 000 lb. per hour was obtained. The unit is in two separate parts, which operate in parallel. The screen boiler, which has a total effective heating surface of 4 276 sq. ft., consists of the four water walls and the one row of tubes over the top of the combustion chamber connecting the rear water-wall header with the steam drum. The water walls are covered from below the stoker to well above the clinker line, with metal blocks bolted to the tubes. The screen boiler has its own separate steam-drum, independent internal-water circulation, feed-water regulator, and other equipment necessary for its operation. The saturated steam from the screen boiler passes to the rear steam-drum of the main boiler. The front water-wall tubes are bent so as to form a Dutch oven over the upper third of the stoker, in order to mix the richer gases with the leaner gases formed at the rear of the furnace. Tests have shown that the screen boiler supplies up to 49 per cent of the total amount of saturated steam produced by the unit. The main boiler, a modified form of the 4-drum Stirling type, located above the screen boiler, has an effective heating surface of 24 234 sq. ft., designed to operate at a working pressure of 455 lb. per sq. in. Saturated steam is discharged from the front and middle steam-drums to the rear steam-drum, from which, with the saturated steam of the screen boiler, it is discharged—through a number of tubes spaced equally across the drum—to the superheater header at a pressure of 409 lb. per sq. in. The superheater, consisting of 52 tubes spaced 6 in. apart, with a total effective heating surface of 4 835 sq. ft. designed to raise the steam temperature to 700° F., is hung vertically from two headers located outside the boiler setting. In order to take advantage of a certain amount of radiant heat, the tubes are placed as near to the furnace as is safe. Protection to the superheater is provided by a row of tubes of the screen boiler and two rows of main boiler-tubes. The economizer is of the bolted-joint, forged return-bend type, with 2-in. outside-diameter bare tubes having an effective heating surface of 6 032 sq. ft., designed to absorb the differences in the amount of heat that would be supplied to the pre-heated air in a pulverized-coal installation and that supplied to the air under present conditions of stoker operation. A soot hopper is located below the economizer and preheater to take advantage of the discharge of fly-ash from the flue gases, which, at this point, make a complete reversal of the direction of flow. The preheater located adjacent to and in the rear of the economizer has 1 920 tubes, of which the effective area of external heating surface is 29 792 sq. ft., reducing the flue-gas temperatures to about 350° F. and raising the air temperature to about the same level. Each unit has two forced-draught fans delivering air at a static pressure up to 12 in. of water. There is one induced-draught fan to each unit capable of providing a static under-pressure of 12 in. of water, with a gas temperature of 350° F. A long straight duct, designed for the complete recovery of the high-velocity energy at the fan discharge, connects the fan to the bottom of the stack. The results of 2 years' operation have shown that the water circulation is satisfactory. The gas temperatures at various locations in the boiler are as predicted. Small adjustments have been made to the baffles to correct the superheated-steam temperature, which now varies between 670° and 700° F. over the range of the boiler loading. It was found that the lagging of the water walls caused an increase of 20° F. in the superheated-steam temperature. The superheater tubes have not been damaged, showing that adequate protection is provided. The boiler economy is very satisfactory and is commensurate with the predicted standard. Still greater economy should be obtained under more favourable conditions of plant loading.

[The author's reply to this discussion will be found on page 601.]

North-Western Centre, at Manchester, 26th January, 1932.

Mr. M. H. Adams: I should like to ask the author the real reason why the Barking and Berlin West stations have given up the use of powdered fuel and gone back to the use of the stoker. While I agree in the main with the basis for boiler-house efficiency given on page 546, I do not like the suggested method of allocating

the auxiliaries. I prefer the more usual method of splitting the two sections of the station on the basis of units generated. The overall efficiency must, of course, be based on output. I do not support the modern tendency to force the boiler plant far beyond the limits of its original design, as I feel that the limit to which the older designs can be taken is being exceeded. This tendency is leading us into difficulties and expense which seem to me out of all proportion to the benefits obtained. Higher steam temperatures and pressures are being adopted in the belief that we can get something for nothing. The increase of temperatures, transfer ratings, and draught must have its effect on the life of the plant. How many of the plants now being erected will be capable of efficient service at the end of 20 years? What we should be endeavouring to do is to generate electricity at the lowest possible cost. The capital charges should be calculated on the basis of the maximum continuous output of the station. In my opinion, the need to-day is for simpler boiler plant with ample surfaces, so designed that the minimum of repairs are necessary. External cleaning should be easily and efficiently carried out whilst the plant is on load, and the plant should be capable of long periods of continuous service.

Mr. S. A. Russell: The difficulties met with in modern stations where economizers are in use have been described in detail by H. C. Lamb and H. L. Guy.* We believe that the trouble is due to the rise in temperature of the water in the economizer during the banked and steam-raising periods. When the boiler is put on to the range the cold water is passed in and the tube is subjected to a drop in temperature of 150 to 200 deg. F. The consequent sudden contraction of the tube may result in a slight leakage which quickly becomes serious. It has been suggested that this difficulty could be overcome by arranging by-pass flues so that during the stand-by and steam-raising periods the gases could be by-passed from the economizer. This system has not been altogether successful in those stations where it has been tried. An alternative suggestion is that during the stand-by and steam-raising periods we should by-pass the water in much the same way as the author suggests we should by-pass the saturated steam through the superheater. This suggestion, however, will probably lead to a serious complication in the feed-water arrangement. I should be glad to know whether the author has any ideas upon how to prevent this trouble. He mentions the use of inert gas in connection with the cooling of the grates and the elimination of the large percentage of boiler outages (Table 12) due to brickwork trouble. The introduction of inert gas has been tried in two or three stations and I believe it has met with considerable success. It gives a more even air distribution, delays combustion, and reduces the stresses on the brickwork.

Mr. V. Walker: Experience in large American stations has proved that the most effective way of reducing the cost of plant and of operation is by the construction of very large boiler units. The average evaporative capacity of the boilers in 25 large American stations is 388 000 lb. per hour, with an average steam pressure of 654 lb. per sq. in. and a total steam temperature of 745° F. The author suggests that the average rate of evaporation per sq. ft. of total heating surface should not be more than 5½ lb. per hour; this figure appears to be very conservative for boilers similar to that shown in Fig. 1, which would give an evaporation of between 16 and 17 lb. per hour per sq. ft. of boiler, economizer, and furnace, heating-surface. I do not think that boilers having a low heat-transfer are less liable to boiler outage than those working at higher rates; this depends, however, on the amount of brickwork in the furnace. The modern design of stoker is capable of dealing with a much greater variety of coal than were former types. Coals with an ash content up to 25 per cent have been successfully burnt on modern grates at the station in which I am interested. There has been no difficulty in carrying the full boiler output without the use of the section of grate next to the dump gear. Large variations in load can be carried by modern stokers without any serious loss through blowing-off. I take it that Table 11 covers wages as well as stoker maintenance, and in that case it compares favourably with some figures I have obtained with the older types of grates. Some of the stokers to which I have referred have been run for 20 months at the very low maintenance cost of 0·15d. per ton burnt. This figure includes all adjustments. The chain grates do not, however, utilize preheated air. I agree with the author that the design of soot-blower equipment could be greatly improved. Soot blowers in the first pass of the boiler are not a success, as they soon suffer from distortion and the nozzles burn away. The so-called " venturi " nozzles in the blower are in my opinion much too large. A high velocity is what is required, not a large volume of steam. It takes 5 000 to 6 000 lb. of steam to blow even a small boiler of 60 000 or 80 000 lb. per hour evaporative capacity. The pressure-drop through the piping is also high; with a drum pressure of 325 lb. per sq. in. I obtained a pressure-drop of 100 to 150 lb. per sq. in. at the blower valves when these were in operation. The maintenance charges are also high. The cross-drum type of boiler is more liable to slag the tubes than the vertical-tube type, and one cannot clean the front row of tubes without taking the boiler off load. I think the velocity of the gases, which may be as high as 50 to 70 ft. per sec. on entering the first pass of many of these boilers, is much too high. With regard to superheater troubles due to the excessive temperature attained on lighting up, we have had trouble on the inlet side of our superheaters owing to internal corrosion presumably caused by water accumulating during banked and lighting-up periods. With regard to the direct-fired versus the central pulverized-fuel system, my experience shows that the two systems have equal efficiencies and reliability with approximately equal maintenance charges, provided there are two mills in the case of the direct-fired system. The latter is easier to handle in many cases, and it gives rise to fewer difficulties due to condensation. I think, however, that the bin system is much more reliable at light loads, and with the unit (direct-fired) system the primary air required for best burner conditions is not always the best for milling. The fineness of the mill product is more even with the bin system. The author is to be congratulated

* *Proceedings of the Institution of Mechanical Engineers*, 1930, vol. 1, p. 603.

on the high boiler efficiency of 88·8 per cent obtained during 1930.

Mr. R. W. Whittle: It is interesting to note that the standard of employee used in America partly accounts for the high efficiency attained there. Changes in design now follow each other so rapidly that by the time a new plant is ready to come into operation it is obsolete, owing to some later improvement. Reliability should be our first consideration. In marine engineering a plant with a high thermal efficiency is of little use if it fails to function when the ship is in the middle of the Atlantic. I am interested to note that the author's experience shows tube-metal temperatures of 900 or 1 000° F. to be near the danger zone. I understand there are in existence superheaters which have satisfactorily operated at a pressure of 400 lb. per sq. in. and have delivered steam at 1 000° F. for periods extending over some months, without any sign of failure. In my opinion the author's circulating system is probably the solution to a great many of the recent troubles in connection with superheaters of similar design to those under discussion. With regard to stud failures; upon the removal of the header, has any fault been discovered in the studs which remained? So far as large boiler plants are concerned, our success in the future will depend entirely upon the degree of generosity with which we view our design. We ought to afford the operator some respite from the continuous anxiety to which he is now subjected owing to the effort necessary to attain present figures of efficiency.

Mr. W. Smyth: I should be glad to have the author's opinion upon the question of pulverized-fuel versus stoker firing, particularly in view of the fact that in the last extension to the Barking station stoker firing was adopted. The author mentions at some length the question of high rates of heat transfer, and in this connection I should like to refer to the Wood steam generator, of which I have had considerable experience. It is essentially a radiant-heat boiler, and an evaporation of 50 lb. per hour per sq. ft. of heating surface is easily obtained. The original trials of the Wood steam-generator showed that without efficient soot blowers it would be a complete failure: the fitting of effective soot blowers has completely altered the outlook for this type of boiler. I am surprised to learn that, by employing compressed air for soot blowing, American engineers can effect a saving of 26·1 per cent, and it would be interesting if the author could give some details of how this figure is arrived at. When Mr. Whittle stated that he was familiar with superheaters working at a steam temperature of 1 000° F. I think he had in mind the Wood steam-generator to which I have already referred, and I should like to add that the superheater tubes of this boiler behaved satisfactorily in spite of this high temperature. If the superheater has to withstand high flame-temperatures the problem of clips presents some difficulty, but this can be avoided by designing the boilers so that the superheater elements hang from the headers. The critical point of mild steel is in the neighbourhood of 600° C., and provided the tubes are not taken above this point no serious harm to the steel need be expected. Referring to the author's remarks in connection with ducting to carry pulverized coal, my experience is that ordinary sheet-steel ducting has such a short life that it is practically useless. Cast iron with reinforcements on all bends should be used as far as possible. Finally, as regards burners for pulverized coal, in order to reduce the capital cost of boilers short-flame burners have been introduced; in my opinion there is room for a good deal of improvement in the design of these burners. I prefer instead the old fish-tail type of burner, or better still the plain pipe which is used for the corner firing of the Wood steam-generator.

Mr. A. Dickinson: I should like to know the comparative costs of pulverized-fuel and stoker plants. The paper indicates that boilers operate for three or four months without cleaning: I presume this refers to pulverized-fuel boilers, and I should like to know whether there is any " birdnesting " on the tubes. If so, how is it removed? We are troubled with " birdnesting " and cannot get it away except by shutting down the boiler. A few years ago I made some interesting experiments on the minimum temperature at which coal will begin to tar or distil. In an atmosphere at 230° to 250° F. a slight smell is noticed, and at 340° F. the gas distils off very quickly. I take it that the grate temperature quoted by the author is the maximum value; if it is exceeded the " cauliflowers " start to form. In going through the grate the air is superheated and instantaneously it " flashes " the surface of each individual nut of coal into tar. The volatile components then begin to come off, and a heavy blanket of coal and coke is formed on the grate. The air cannot get through this blanket, and the only remedy is to break up the coal bed. I have done this by turning off the preheated air for half an hour, also by putting plenty of water on the coal at the affected spot. The former method is the quicker. With reference to steam pressures, in America about 600 lb. per sq. in. is used for one set of work, and 1 300 lb. per sq. in. for another set. This country will probably settle on 800 to 900 lb. per sq. in. for turbines and 1 000 lb. per sq. in. for boilers. At these lower pressures steam has a maximum heat content per lb. when saturated. The superheater temperature has to be adjusted to suit each particular installation. On our plant not one superheater tube has failed during the 7 years' life of the plant, although we run them at from 800 to 840° F. The only trouble we have with superheater tubes is a slight sweating or oozing at the expansion joints. Internally the tubes become coated with a red oxide, but this protective coating stops further corrosion. With regard to the efficiencies given in Table 1, the stoker efficiency at Richmond is 87 per cent, and the figure for the best pulverized-fuel plant is 87·3 per cent. It would be interesting if the author could give the boiler-house load-factor and the size of the boilers, as this would enable one to obtain a better idea of the relative merit of the two systems. The turbine size is limited to 14 000 kW for the extra-high-pressure plant, and turbine makers are at present a long way from producing 30 000- to 40 000-kW turbines working at pressures of 1 000 or 1 200 lb. per sq. in. As to the two sets of tests on No. 15 boiler unit (Tables 2 and 3), the 3 per cent gain in efficiency after 12 months was probably due to the fact that better-quality coal was

used on the second test. My own experience shows that good-quality coal is essential for efficiency. Poor coal often gives rise to bad combustion conditions over which the fireman has no control.

Mr. G. A. J. Begg: The author's figures of steam evaporated per pound of coal are given to three places of decimals, despite the fact that the possible errors involved in arriving at these figures render the third decimal place of doubtful accuracy. Although he gives his fuel analyses to the second place of decimals, it is unlikely that the whole of the fuel fired on to his boilers during the period of the test was so accurately sampled as to justify such an order of accuracy. Seeing that in general the fuel proportion of the cost of a unit is in the neighbourhood of 25 per cent, improvement in boiler efficiency from 80 to 85 per cent only reduces the unit cost by about 1 per cent, and this can very soon be lost if to attain it means increasing the capital cost of the station. Although in America the tendency for the last 10 years has been in the direction of bigger units, higher pressures, and higher ratings, at the present moment the trend of development is definitely in the other direction. With regard to the burning of coal on chain grates, we have investigated the damage that this does to the grate surface of ordinary travelling-grate stokers. As the result of a large series of measurements of the temperature of the bars forming the grate surface, we found that up to the nose of the arch the temperature remains approximately the same as that at which the bar enters the furnace. As soon as the bar gets beyond the distillation zone, however, the temperature rises rapidly in a manner depending upon the nature of the firing. In order to reduce the maintenance costs of the grates we tried using special types of heat-resisting cast iron for the bars, but little improvement resulted. The second method of attack was to increase artificially the ash content of the fuel and so form a protective layer on the surface of the grate bar. This was partly successful, but it had several disadvantages. Finally we attacked the problem from the design point of view, and came to the conclusion that the temperature of the grate bar was the equilibrium value corresponding to a balance between the heat received from the fuel bed and the heat conducted away into the air passing across the sides of the bars. We deduced from this result that the criterion for a successful inset piece would be the ratio between the burning surface and the surface exposed to the air passing by. This ratio should determine in some measure the actual temperature reached. We increased the ratio from 1 : 3 to 1 : 14, and also developed the shape mathematically to give a correct thermal balance. This experiment was successful, for a microscopic examination of the iron of the new design showed perfectly clearly that there had been no overheating. Unfortunately, the cost of the new design almost precludes its use. The author's statement regarding the addition of "inert" gas to the air supply for reducing the fuel-bed temperature is unfortunate, because the gas is not really inert. We take flue gas (containing CO_2) from the back of the boiler and pass it through the fuel bed with the air. Immediately the CO_2 meets the coal at the bottom of the fuel bed, it is, I think, reduced to CO. This reaction, being endothermic, results in a definite cooling of the fuel bed at the grate surface. The CO becomes oxidized again to CO_2 in the upper portion of the furnace. Turning to the subject of soot blowing, has the author had any experience of the use of water jets for preventing the growth of "bird-nesting" in boilers? Unfortunately he does not go into the question of the most suitable type of refractory for use in combustion chambers, a question of prime importance to the users of high-duty boilers.

Mr. D. L. Thornton: I should like to suggest a close scrutiny of the figures given in the paper, because there seems to be some doubt about what really constitutes thermal efficiency. When testing boiler plants in America I found time after time that the efficiencies claimed had to be reduced by 15 to 20 per cent. In general American engineers use higher temperatures than we do, and German engineers are inclined to use higher pressures. English practice lies somewhere between the American and German ranges. We use moderate temperatures and pressures. I agree with the author that the radiant-heat process of transmission is becoming an increasingly important matter in modern boiler design, and it is linked up with the problem of the shape of the combustion chamber.

Mr. A. L. Timmins: To some extent the troubles experienced in England with pulverizing equipment have been due to the fact that British coals represent a much wider range than American coals. Almost every type of coal dealt with requires special consideration. The maintenance costs of various plants which have so far been published are rather misleading because they include the cost of experiments and improvements. This is borne out by the figures quoted in the paper, which show a reduction in maintenance cost in 1931 as compared with 1930, although one would expect an increase as the plant wears. With regard to the trend of pulverized-fuel firing, the fact that the unit system is generally preferred to the central system suggests a confidence in the reliability of the former which was not felt five or six years ago. At the same time, the experience at the author's station, where no outages have been caused over a period of years through failure of pulverizing equipment, is an argument in favour of the bin-and-feeder system rather than an indication that the pulverizing plant is completely reliable. Dealing with the permissible rate of evaporation, by taking more advantage of radiant-heat absorption it would be possible at least to double the figure which the author regards as the safe limit. The radiant-heat boiler referred to by Mr. Smyth goes a long way towards overcoming some of the other criticisms of modern boilers. The high efficiency of radiant-heating surface, in comparison with convection surface, leads to a reduction in the number of passes, and it also enables the superheater to be arranged on the inter-deck instead of the inter-tube principle; the former provides greater latitude for accommodating the required surface, and at the same time makes it more accessible for cleaning purposes. I am surprised that the author makes no mention of automatic control. Experience gained in connection with automatic control of pulverized-fuel plants shows that it goes a long way towards ensuring

continuous high efficiency with boilers of high rating. As to the maintenance cost of pulverizing equipment, we in England have been guided by the experience which America obtained with coal of different quality from our own, and small modifications such as a slight reduction in the speed of the mills might tend to reduce the maintenance cost more considerably than we are inclined to suspect. The wide range of operating costs shown in Table 5 may be accounted for by the fact that anthracite was being used at the two stations for which high figures are shown, and the abrasive qualities of this fuel may have had a deleterious effect on the mills.

[The author's reply to this discussion will be found on page 601.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 7TH MARCH, 1932.

Mr. P. J. Robinson: The design and operation of boiler-house plant has a very important influence on power station costs. With regard to the question of pressure (page 543), the present tendency towards extremely high pressures has very often, I think, been dictated more by a desire to be up-to-date than by a careful consideration of the effect on overall cost. When the conditions for Clarence Dock power station were being settled it was found that with a steam temperature of 775° F. at the boiler the net saving achieved, i.e. the difference between reduction of fuel cost and increase of fixed charges, would be less than 0·001d. per kWh by going to a pressure of 580 as compared with 400 lb. per sq. in., and that this saving would disappear if the pressure went up to 800 lb. per sq. in. These values were based on a load factor of 60 per cent, a fairly high figure even for a base-load power station. Any unexpected trouble would very soon turn this saving into a loss. In addition, unless an excessively high steam temperature is used a higher pressure than 400 to 500 lb. per sq. in. will produce excessive wetness at the low-pressure end of the turbine, unless reheating be adopted. This latter complication is in my opinion not altogether desirable. It was therefore decided to use a moderate pressure, 450 lb./sq. in. being the figure adopted for the boiler pressure. It is interesting to note that very much higher pressures occur in the feed-ranges, where there may be an excess of 150 lb./sq. in. above the boiler pressure. This necessitates careful attention to the setting of economizer safety-valves. While I am in agreement with those who recommend the use of high steam temperatures, I do not think that sufficient prolonged experience has yet been obtained of metals subjected to high temperatures to justify figures exceeding 800 to 825° F. With this in mind the plant at Clarence Dock was designed for an initial steam temperature of 750° F., but provision was made for raising the total temperature to 825° F. at a later date, if necessary. On page 549 the author refers to a station efficiency of 24·4 per cent achieved in America: an investigation of the possible Rankin-cycle efficiency of plant shows that—even allowing for losses in the boiler plant, steam ranges, turbine, and alternator—the station efficiency should be of the order of 27 per cent. There is consequently a constant loss of 10 to 15 per cent which is apparently unaccounted for. This loss, I suggest, is entirely due to load fluctuations. I do not agree that pulverized-fuel firing will give a higher boiler efficiency than properly-designed combustion chambers fired by mechanical stokers. Dealing with the question of the size of combustion chambers, it is not long since the axiom of boiler designers appeared to be the setting of boiler tubes as close as possible to the grate. In 1924 we realized that so long as this arrangement was adopted high boiler efficiencies could not be obtained, and that the higher efficiencies claimed for pulverized-fuel firing were entirely due to the large combustion chambers peculiar to that system. A section of boilers in the Lister Drive No. 2 station of the Liverpool Corporation supply undertaking were therefore altered, the lowest row of tubes being raised from 3 ft. 6 in. to 7 ft. 6 in. above the grate surface. Whereas it had previously been impossible to obtain the rated evaporation of 20 000 lb. per hour with these boilers, after the alteration 40 000 lb. per hour was regularly obtained without difficulty, and the increased efficiency, absence of smoke, and reduction of "birdnesting" were very marked. The advantages of this alteration were not immediately appreciated by the boiler designers, and although they were responsible for putting in boilers at one large modern station with tubes at an average height of 9 ft. above the grate, it was suggested by them that the arrangement adopted in the Lister Drive No. 3 station of having an average furnace height of 14 ft. was needlessly expensive. This is a cooling-tower station, and the fact that the thermal efficiency per unit generated over a year's running was 20·36 per cent is ample evidence of the advantages of the high combustion chamber. In the Clarence Dock power station the average height of the tubes is 22 ft. from the grate surface, the increase above the Lister Drive setting being mainly designed to accommodate pulverized-fuel burners in the sides of the combustion chambers. On these boilers pulverized fuel is used in conjunction with stoker firing, in order to obtain the benefit of cheaper fuels and also to meet sudden demands for steam. Although the refractory problem is referred to by the author, he does not emphasize what in my experience is the most satisfactory way of dealing with this, namely, by the use of Bailey blocks. When the Lister Drive No. 3 station was first put into operation the problem of the maintenance of refractories was very serious. The arches were of the sprung type, and it was soon found that operation with a reasonably high CO_2 content resulted in failure of arches within 10 or 12 days, thus rendering economic working impossible. A number of experiments were therefore carried out with the aim of increasing the life of refractories. Air-cooled arches and side walls were tried out, but although a longer life was obtained with these they were not entirely satisfactory. At this time the installation of further boiler plant in

Lister Drive No. 3 power station was under consideration, and as a result of a tour of the principal power stations in this country and abroad, and an investigation of various possible arrangements, it was decided to lay down three boilers fired with pulverized fuel on the unit system. The furnaces were entirely lined with Bailey blocks, this being the first installation of the kind in this country. The results obtained amply justified the initial extra expense of the blocks, as in the 4 years since this plant was put into operation only 2 out of the 23 025 blocks have had to be replaced. In each case the trouble was due to a broken stud. A further advantage of the use of these blocks is that their heat content is less than that of ordinary firebricks, and this heat is more readily given up to the water in the boilers, with a consequent reduction in the losses when the boilers are put on and taken off the range. The firing of these boilers on the unit system has proved entirely successful, and as a result of my examination of various plants I am convinced that this is the only satisfactory system of pulverized-fuel firing. In view of the results obtained at Lister Drive, Bailey blocks were installed on the side walls and front and rear arches of the combustion chambers at Clarence Dock power station, and although it was suggested that the use of these blocks in the front arch would, by overcooling the furnace, reduce the efficiency to a low value, experience has proved that these boilers can be regularly run with a CO_2 content of 15 per cent. On page 554 the author refers to the outage periods of boilers, but the percentage figure which he gives does not include the period of annual survey and overhaul which is part of the outage. My experience has been that his figure of 6 to 8 weeks for annual survey and overhaul is excessive and that 4 weeks is adequate, but it is possible that the use of Bailey blocks has assisted in obtaining this lower figure. In connection with the use of compressed air for soot blowing (page 558), I should like to state that the first compressed-air soot-blowing system installed in this country was the compressed-air hand-lances at the Lister Drive power station, which have been used for the last 16 years. Although the plant in Lister Drive No. 3 station was operated with steam blowing, the drawbacks of this were found to be so considerable that it was decided to use compressed air at the Clarence Dock power station, which has the first modern plant of this type in Great Britain. The disadvantages of steam blowing are: first the energy lost is 3 times that lost with compressed-air blowing, secondly a considerable number of tappings are required on the high-pressure and steam ranges, and thirdly the boiler-feed make-up reaches such a high percentage as to necessitate the use of large evaporating plant. In this connection it is interesting to note that the use of compressed air for soot blowing at Clarence Dock has reduced the boiler feed make-up to less than 1 per cent. At this station the supply of compressed air is obtained from a turbo-blower driven by a 3 300-volt motor. The present tendency towards increasingly high draught renders the forced- and induced-draught plant more and more important. The adoption of the usual overload of 25 per cent on the normal boiler rating necessitates the installation of fans and motors very much larger than those required for normal working, and at the Clarence Dock power station it was therefore decided to install draught equipment designed only for an overload of 10 per cent. This decision led to a very considerable saving in the cost of fans, motors, and transformers. Even with this reduction in size the motors are still large, and advantage has been taken of this to utilize motors supplied at 3 300 volts, with a consequent saving in cable sizes and copper losses. The question of draught control is very important. Direct current is now rarely used for draught-fan motors in power stations, and variable-speed a.c. motors are expensive. The draught is therefore usually controlled by means of dampers; this arrangement is not only uneconomical but is also responsible for a large amount of the erosion which takes place in the induced-draught fans. The Lister Drive No. 3 station was the first in which a hydraulic coupling of the Vulcan-Sinclair type was utilized for induced-draught fans. The coupling was found to be so satisfactory and it resulted in such a considerable saving in power that similar couplings were used on all the forced- and induced-draught fans at Clarence Dock. The readiness with which the speed, and consequently the draught, can be controlled, makes these couplings particularly suitable for the adoption of automatic control, and the Clarence Dock power station is the first in the country to have automatic boiler-control equipment working on hydraulic couplings.

Major W. Gregson: The author is a little drastic in limiting his evaporation to 5·5 lb. per sq. ft. of heating surface. Boiler design is developing so rapidly that, provided adequate circulation is ensured, much higher ratings can be worked to with complete immunity from maintenance troubles. It is purely a question of design, and a figure which would be low for one boiler might be nearly the limit for effective running with a different design. I should like to emphasize the desirability of the water-walled furnace with stoker firing, and to correct the erroneous impression that pulverized-fuel boilers alone benefit by a water-walled construction. The great advantage of the Bailey furnace is its automatic adjustment to operating conditions; at all loads it avoids slag troubles and yet does not cause quenching of the combustion. The company with which I am associated is engaged in research work on the question of superheater design for high temperatures, and it appears that the demand for still higher temperatures will be met jointly by metallurgical developments and advances in connection with siting. From the point of view of efficiency there is little to choose between pulverized-fuel and stoker firing. For large boilers the retort-type stoker, used with suitable fuel, is likely to become popular. The fact that the modern water-tube boiler maintains continuously efficiencies of 85 to 90 per cent leaves little room for improvement on the thermal-efficiency equation.

Mr. J. Hamilton: The author points out that high efficiencies are only of academic value, and I agree that they can be obtained at too great a cost. Table 1 indicates that the stoker plant of the Richmond station of the Philadelphia Electric Co. has an efficiency comparable with those of the pulverized-fuel stations. As

banking losses are greater on stoker-fired than on pulverized-fuel plant it would appear that the efficiency of this station is higher than that of the pulverized-fuel stations. On page 544 the author mentions combustion rates of 70 to 80 lb. per sq. ft. of grate area: are these rates in use in actual practice? So far as I know they have only been obtained from an experimental plant on a freak setting not applicable to modern boilers. If such rates can be obtained, the author's figure for the limiting capacity of stoker-fired units will almost be doubled. With reference to the retort stoker, I have always had the feeling that with the class of fuels available in this country there might be considerable difficulty in getting good combustion in this type of stoker. I do not agree with the author's method of arriving at an availability factor. All boilers must be laid off for an annual survey, and the outage period should be fixed. To my mind 15 days only are necessary for a complete survey and overhaul of the mountings of modern boilers, and any other work required at that time should be debited to repairs and maintenance outage. If the denominator of the equation is taken as 8 400 hours all plants will be placed on a comparable basis. According to Table 12, the total available hours for Boiler No. 22 were 7 977; I cannot reconcile this with the chart shown in Fig. 4, which indicates that Boiler No. 22 was in course of erection for the first 3 months of the year, and was only available for the remaining 9 months. The figure in question should be about 6 600. I am in agreement with the author as to the desirable rate of evaporation. The figure for our boilers at Clarence Dock power station works out at 5·5 lb. per hour per sq. ft., rising to 6·1 on the overload rating. The method shown in Fig. 8 has proved quite successful at Clarence Dock for overcoming "bird-nesting." This has been one of our biggest bugbears at Lister Drive, but we are getting over the trouble. Two of the boilers at Clarence Dock power station are equipped with speed-reduction equipment of the infinitely-variable type. I agree with the author that too often ducting consists of sheet-metal work which would disgrace a tinsmith. All ducting should be of welded construction and made of heavy plate with no internal projections such as rivet- or bolt-heads. All flanges should be external and so constructed that a dustproof joint can be made. With regard to dampers, a great deal of pressure may be lost if these are badly designed.

Mr. H. Midgley: I should be glad if the author would explain the term "cold fraction of five-sixths" used on page 548, as this expression is new to the majority of engineers. On page 557 he states that the development resulting in practically all the boiler heating surface becoming a water-tube cage surrounding the furnace has limitations, as at present it can only be adopted in conjunction with pulverized-fuel combustion equipment. I suggest that this wording does not convey the meaning intended, as literally interpreted it would rule out the use of stoker-fired boilers having the four walls of the combustion chamber water-cooled, whereas this construction is adopted in the boilers at the Clarence Dock power station of the Liverpool Corporation. The front, rear, and side walls of these boilers are completely water-cooled and protected with Bailey blocks. Regarding the statement (page 577) that "the wires or chains connecting dampers to their controls should not be visible," such a procedure would result in the wires or chains not receiving the attention and maintenance necessary for satisfactory operation. Whilst they should be so arranged as neither to block passage-ways nor be unsightly, they should, I think, be visible for as much of their length as possible. No reference appears to be made in the paper to what I regard as one of the most satisfactory systems of boiler firing, namely the combination of pulverized fuel and mechanical stokers. About five years ago at the Lister Drive (No. 3) power station of the Liverpool Corporation, a Yarrow boiler normally fired by means of a chain-grate stoker was equipped with two burners in the sides of the combustion chamber, supplied with pulverized fuel from a unit (Atritor) mill. This arrangement enabled the evaporation of the boiler to be raised 40 per cent within 3 minutes of first switching on the mill motor. No trouble was experienced in lighting-up, the fire on the chain grate being adequate for this purpose. The evaporation returned to the normal value immediately the mill was stopped. The advantages of such an arrangement for meeting unexpected demands for steam due to sudden clouds or breakdown of plant, and also for the utilization of cheap fuels, will be obvious. In view of the results obtained at Lister Drive a similar arrangement has been adopted at the Clarence Dock power station. I understand that boiler manufacturers in this country are giving careful attention to the reduction of the number of passes of the flue gases through the boiler tubes. This type of development should be encouraged because of the resultant simplification in design and the reduction in draught losses.

Mr. A. L. Timmins: I shall refer first to the author's conclusion that pulverized fuel is at present in disfavour. Although there are at present under construction a larger number of stoker-fired than pulverized-fuel boilers, the evaporative capacity of the pulverized-fuel-fired boilers now under construction in this country or recently put into service exceeds 2 000 000 lb. per hour, or (say) 60 000 h.p. Turning to the comparison of British and American super-power stations, I think that the author's list should be supplemented by the addition of Kirkstall station (50 000 kW) and the high-pressure boiler plant of Imperial Chemical Industries at Billingham. Referring to Tables 4 and 6, has the author any figures to show the amount of coal used at his pulverized-fuel station for lighting-up and banking purposes? If such figures were available it would be possible to determine to what extent elimination of lighting-up and banking losses contributes to the economy of pulverized-fuel firing. The figures quoted for Deptford power station show that approximately 2 per cent of the loss of efficiency is due to coal used during banking periods. Assuming even that banking losses with pulverized fuel are negligible, the inference is that pulverized-fuel firing can still show an efficiency of 3 per cent in excess of modern stoker practice. According to published figures, the Kearsley station is the most efficient in this country. The conclusion to be drawn from the paper is that its overall thermal efficiency might be increased by 1½ per cent if the boilers were

fired by pulverized fuel. As an instance of extreme reliability I should like to refer to the pulverized-fuel plant at York Street Flax Mills, Belfast; this consists of a single boiler which has been in service since 1926 and has met all the requirements of the mill. Any necessary reconditioning has been carried out during week-ends and ordinary public holidays, and it is doubtful whether any other plant could show a better reliability factor. Regarding the author's statement that completely water-cooled furnaces are only applicable to pulverized-fuel firing, while it is true that the steam-generator proper has so far only been operated with this system of firing, with the development of archless stoker settings the design of stoker-fired boilers is tending towards the same construction. The author's figure of 5 to 6 lb. per sq. ft. of steam per hour for the maximum rate of heat transfer is very conservative, and judging by developments during the past 12 months 10 to 12 lb. per sq. ft. per hour would be perfectly reasonable and safe. The new-type pulverized-fuel-fired boilers now being installed at Brimsdown power station deal with 10 lb. of steam per sq. ft. per hour, and operate with air heaters only.

Mr. E. B. Pausey: Three years ago we added two pulverized-fuel boilers to our stoker-fired boiler installation. I felt some regret when this course was decided upon, because it seemed to me that a good deal of valuable experience accumulated during many years' operation of stoker boilers was going to be wasted. I had been led to believe that the new boilers would be so simple and easy to operate as to render previous experience superfluous, but within a week from the date when the new boilers were set to work I had reason to modify that opinion. Serious troubles were frequent, and we could never depend upon the boilers. As a result of successive improvements, however, we can now regard our pulverized-fuel boilers as one of the best assets of the station. We are able to burn at a high efficiency a very cheap grade of coal which does not exceed $\frac{1}{4}$-inch mesh and whose ash content is very high, often reaching 30 per cent. "Birdnesting" was a frequent cause of outages in the early stages; it was found to be due to too high a gas velocity at the first pass. An entire cure of the trouble has been effected by a drastic reduction of the height of the baffle in the first pass, and by careful attention to correct combustion conditions and the use of the soot blowers. The author refers to the desirability of slightly sloping the tubes in water walls so as to minimize risk of failure by bulging, but my experience is that vertical tubes are entirely immune from this trouble provided that the circulation is unimpeded. The existence of scale in these tubes, detrimental though it may be in other respects, does not cause bulging; indeed, I am of the opinion that to some extent it prevents this trouble. The essential point is to enable the steam to get away from the tubes as soon as possible after it has been formed. In view of the large amount of grit in pulverized-fuel boilers the grit arrestors should be placed in front of the induced-draught fan and as near as possible to the boiler, otherwise much trouble will be experienced from extremely rapid erosion of the fan and the ducts leading to it. The possibility of the pressure parts of the boiler being slowly sand-blasted by the grit should not be overlooked by boiler designers. I have met with two instances of tube failures by erosion due to this cause, aggravated by improper arrangement of soot blowers.

Mr. C. P. Parry (*communicated*): The paper suggests that in this country, at any rate, the correct application of soot-blowing apparatus is a long way from finality. In my opinion this is due to the fact that every manufacturer of boiler adjuncts makes himself responsible for the soot blowing of his own particular part; thus there may be as many as three different makes of soot blowers on the same plant. The critical parts of a boiler plant, from the soot-blowing point of view, are the superheaters, economizers, and air heaters. No soot blowers can give the best results on any part of the plant unless the operation of these parts is on certain established lines. Soot blowing is a specialist's job, and it is satisfactory only when that specialist is allowed to treat the whole plant. I agree with the author that soot-blower operation, if it is to be fully effective in the maintenance of clean surfaces, is necessary at least 3 times in 24 hours. This applies more particularly to the rows of tubes nearest to the combustion chamber on which "birdnesting" first forms. I cannot agree, however, that increasing the vertical or horizontal pitches of tubes near the combustion chamber has any effect in preventing birdnesting in the first boiler pass. I also do not agree that the use of high steam-pressures necessitates more costly blower equipment. My firm have supplied blowers for pressures up to 800 lb. per sq. in. at the same cost per blower as for lower pressures. As far as I know, the only air compressor used for supplying permanent blowers in this country has cost as much as a complete steam-blower equipment for about six boilers, and that in addition to the cost of the air blowers themselves. Contrary to the author's view, I consider that feed make-up is not appreciably increased by a system of steam blowers which efficiently utilizes steam at a high pressure such as that in the main turbines. With regard to "birdnesting," the first deposit on an internally-clean water tube is of a granular and friable nature, owing to the molten particles of ash being cooled below their fusing point before they can actually impinge upon the tube. If the granular deposit is blown off the tubes before it becomes so thick as appreciably to insulate the metal from the approaching molten ash, birdnesting never occurs. If the granular deposit is allowed to remain on the tube until it has attained sufficient thickness, further deposit collects in a fused state around it. An effective steam blower will, however, remove the birdnesting for at least two rows of tubes from the furnace, provided there is a granular layer in contact with the metal. If a single water-tube were isolated in the middle of the combustion chamber, the ash would probably form in a fused state in intimate contact with the metal, and then a blower would have no more effect on it than it would have on ash fused solid with brickwork in a combustion chamber. It appears to me that the larger the amount of water-cooled surface exposed in proportion to the weight of gases and of incandescent ash approaching the surface, the more certainly will the ash be cooled below its fusing point before impinging upon the metal. Increasing the horizontal pitch of tubes next the combustion chamber

will reduce the cooling surface in the first row, and this will render the formation of fused ash near to the metal more likely. If the vertical pitch is increased, the cool zone created by the surfaces in the second row does not assist to the same extent in cooling the gas approaching the first row, and there is more tendency for fused ash to form near the metal in the first row. In the early days of the operation of the boilers, one of which is shown in Fig. 3, the blowers were only used in the hours of darkness, which meant intervals of 12 to 16 hours. Even under these conditions boiler No. 15 ran 6 weeks continuously under full load, and at the end of that period there was no sign of birdnesting in the pass, which was perfectly clean from the combustion chamber right up to the top, including the superheater. The boiler ran for another week with an overload, but could not steam any longer because the pass was then choked with birdnesting. Although the steam blowers were capable of removing the birdnesting from the lower two or three rows, they could not remove it from rows higher up; if the blowers had been used, say, every 4 hours, the boiler would have worked indefinitely without trouble from birdnesting, even on overload. Birdnesting can only form on higher rows when the lower rows are foul, so allowing high-temperature gas to penetrate further up the bank. If birdnesting is allowed to form beyond the third row, blowers can only clean the lower rows so long as there are gas passages to blow through beyond the third row; but as soon as a portion of the pass chokes at the third or fourth row, the lower rows must choke also. On similar boilers, 4 ft. less in width, at a power station in the Midlands, the lower tubes have widened pitches to form a slag-preventing screen. Following the ideas expressed above, I fitted four blowers to the first pass of these boilers. Experience has proved that these are necessary, and that they must be used every 4 hours if there is to be no birdnesting. The deposit formed on a boiler immediately after banking periods is, in my experience, much more adhesive than that formed during ordinary steaming periods, and therefore the blowers for the second and third passes are necessary. However, they need not be used so frequently as those on the first pass or on the economizer. I was interested in Mr. Robinson's remarks regarding the raising of the boilers at Lister Drive, and I agree that this alteration, by increasing the combustion space, would render the conditions somewhat less onerous for the steam blowers. The gas distribution is more uniform through the first pass, there is less intense bombardment of the tubes with fly-ash in certain zones, and the heavier particles drop on to the grate. I fitted nine of these boilers with blowers, and there was no difficulty in preventing birdnesting—either on the one boiler working at 20 000 lb. per hour or on the eight boilers working at 40 000 lb. per hour. I recently fitted a set of sixteen blowers to one of the pulverized-fuel boilers at Lister Drive. The boiler has been steaming since the beginning of October 1931, and practically no hand cleaning has been done on it as no trouble from birdnesting has occurred. The steam consumption of the blowers on this boiler amounts to 0·43 per cent of the weight of water evaporated, taking this as 126 000 lb. per hour.* Corrosion of air heaters is, in my view, almost entirely caused during lighting-up, or re-raising of steam, and it can be prevented; but if compressed-air blowers are used the corrosion will be greatly intensified and become uncontrollable. Some air heaters that I have been consulted about, on which air blowers were used during steaming periods, have had to be cut out of the plants owing to corrosion and choking. Unless a costly heating arrangement be incorporated in the air-compressor plant, the air must enter the boiler-gas passages at temperatures considerably below the freezing point of water. Finally, I should like to point out that the American figures for the operating costs of steam blowers are 4 to 5 times as large as those shown by many power stations in this country.

[The author's reply to this discussion will be found on page 601.]

Western Centre, at Cardiff, 14th March, 1932.

Mr. J. B. J. Higham: In reports of boiler tests one not uncommonly finds a figure such as 90·47 per cent given for the efficiency, which suggests that an accuracy of measurement to at least 5 significant figures has been attained in all test work. This, I suggest, is absolutely impossible. The quantity which it is possible to determine most accurately is without doubt the calorific value of the fuel. Experts of the Fuel Survey Laboratories obtain check results for the calorific value of carefully sampled coal to the third significant figure: e.g. a South Wales bituminous coal will have an average value of, say, 13 510 B.Th.U., subject to an error of ± 10 B.Th.U. The fourth figure may be 2, or 0, giving a possible variation of approximately ± 0·075 per cent. Other quantities, e.g. pressure and temperature, obtained on a boiler test are subject to errors of at least ± 2 per cent. Boiler-test results will, in all probability, be correct to the second significant figure.

Mr. A. Nichols Moore: The paper can be considered from two distinct points of view, namely that of the engineers who are responsible for specifying and installing boiler plant, and that of those whose work it is to operate the plant. The author devotes himself almost entirely to the second alternative. I am surprised to find that he makes hardly any mention of capital charges, and it would be interesting to know the reason for this omission. Speaking generally, the experience that has been obtained in this country with pulverized-fuel installations has not been altogether happy. The available information relating to the latest installations which are being put down in this country, including that at the station with which the author is associated, indicates that those competent to form a considered opinion have come to the conclusion that stoker-fired installations are to be preferred in this country. Many of the serious difficulties met with in connection with the

* The steam used by efficient blowers is usually from 0·2 to 0·3 per cent of the weight of water evaporated.

use of pulverized-fuel plants in Great Britain have been the result of lack of experience on the part of those responsible, and lack of knowledge of the conditions over here—particularly in regard to suitable coal—on the part of those who introduced the plants into this country. There are one or two detail points in the paper to which I desire to refer. First, I should like to know why the cost of furnace brickwork for the Hams Hall station is omitted from Table 10. In Table 11 the author gives some particulars of maintenance costs for power-station boiler plant equipped with travelling-grate stokers. It would be interesting to know the date to which these statistics refer, as stoker-fired boiler plants of modern design give much higher overall thermal efficiencies than 79·41 per cent. In the station for which I am responsible the official test figure—correctly taken on a 60 000-lb. per hour unit equipped with chain-grate stokers, economizer, and primary and secondary heaters—was over 87 per cent. With regard to Tables 12 and 13, it is curious that the author does not take the trouble to work out the availability factor of the stoker-fired boilers. In the case of No. 3 station unit I find the availability factor to be of the order of 86 per cent (after making due allowance for the annual cleaning period); this figure compares very favourably with the particulars given in Table 12. In conclusion, I desire to make a brief reference to the possibility of the development of pulverized-fuel installations in the South Wales area. So far little has been done, and I believe that what has been achieved does not justify an optimistic outlook in regard to further developments. For my own part I am satisfied, after taking all possible factors into consideration, that a better case can be made out for stoker-fired installations. In the western area, however, where exceedingly low-volatile coals are more generally available in the immediate vicinity, and where the use of the higher-volatile coals from the Monmouthshire coalfields would add unduly to the cost because of transport charges, some development of the pulverized-fuel system may succeed, and we shall await with interest any progress in that direction.

Mr. H. F. Reeman: I do not subscribe to the view, expressed on page 553, that the reliability of the large modern turbo-alternator and its auxiliaries has reached a degree far in advance of that inherent to the boiler unit. I suggest that the performance of the boiler unit is hardly comparable with that of the turbo-alternator, as during normal running periods the latter is not affected to any extent by the human element, and, given the initial and terminal conditions, there is little to worry about from the point of view of operation. For the boiler unit, on the other hand, the conditions are not quite the same: the temperature of the furnace is far higher than that of any part of the turbine, and, further, in the case of refractory-lined furnaces burning fuels having low ash-fusion temperatures damage to the refractories can be readily brought about by any error in judgment in regard to operation. The fusing point of the ash is usually the most important controlling factor in establishing the rate of combustion, correct amount of excess air, labour of operation, and cost of furnace maintenance, for a given design of furnace; this factor also has a bearing on the number of boiler shutdowns necessitated by brickwork failures. In the present-day design of boiler unit, however, incorporating water-cooled furnace walls and a covering of refractory-faced or plain cast-iron blocks in intimate contact with the tubes, boiler outages for brickwork repairs have been entirely eliminated. With regard to the pulverized-fuel system, this has been improved so much recently that in some cases it is now as efficient as stoker firing. I do not consider, however, that the pulverized system is the only successful method of burning fuel under boilers.

Mr. J. W. Burr: It is interesting to note that in America most types of coals are supplied to the generating stations as lump or run-of-mine, free from dust and smalls, the subsequent crushing and handling being designed to deliver a uniformly-graded product. This does not seem to me to be an economic proposition, as the higher cost per B.Th.U. in the coal would probably more than counteract any slight increase in furnace efficiency, due to uniform grading. In the pursuit of increased efficiency of steam power plant, steam pressures have been increased. At the present time 600 lb. per sq. in. seems to be regarded as the most economical pressure, taking into consideration the points mentioned by the author. The steam temperature will remain at its present value of about 800° F. until metallurgists produce a metal which will withstand a higher temperature satisfactorily under working conditions. It is interesting to note that the Detroit Edison Co. are putting into commission a plant to operate with a steam temperature of 1 000° F. I think the author should have stated that the experimental plant to which he refers was made in the British Isles. His statement that travelling grates have reached a stage of development which permits their adoption for boiler units up to 250 000 to 300 000 lb. per hour, is hardly correct in cases where coal with a low volatile content is used. With reference to the question of the elimination of the refractory in the combustion chamber (page 546), would not the volatile content of the coal again have to be taken into consideration? Is it not possible that when burning coal with a low volatile content (say, 8 per cent) refractory blocks would have to be used for encasing the water walls? I am interested in the author's remark on page 553: "Generosity in design does not necessarily mean an increase in first cost for a given capacity," and I should like to know under what conditions it is possible to obtain a boiler generously designed at the same first cost as the higher ratings. The chief object of the modern tendency towards higher rates of evaporation per sq. ft. of heating surface was, I had thought, that of reducing the first cost of the boiler. While I agree that in order to obtain reliability and high thermal efficiency over long periods a generous apportionment of heating surface is necessary, it seems to me that the author's figure of 5·5 lb. per hour for the average rate of evaporation per sq. ft. of total water heating and evaporating surface at normal loads, is low. If this figure were adhered to we should need larger plant than is absolutely necessary for a given load. I should like to know the cost of compressed-air soot-blowing apparatus, as this seems to offer greater possibilities than the steam soot-blower. Dealing with pulverized-fuel firing, does the author prefer the bin-and-feeder system to the unit

system? Although the unit system should cost less to install, is it not possible to more than cover the additional annual charges on the expenditure by a reduced cost of milling? I am given to understand that the greater degree of flexibility of the bin-and-feeder system enables this to achieve a saving of as much as 3d. per ton of coal pulverized under certain conditions. The question of fuel fineness deserves further investigation, especially in connection with semi-anthracitic coals. Would any practical difficulty be experienced in obtaining a fuel fineness of 85 per cent through a mesh of 200 to the inch?

Mr. S. M. Hill: In Table 3 (page 550) the loss due to carbon in the ash is given as 0·22 per cent. I should welcome the author's comments on this extraordinarily low value. Regarding reliability, I agree that too little attention is paid to the details of construction of modern boiler plant. While the boiler itself is usually sound mechanically, the importance of the design and lay-out of the combustion and gas side of the plant is too often overlooked. The question of how to lay out the plant so as to ensure ease of operation is of great importance. Turning to page 557, the ability of a clean boiler to pass its guarantee trial is no criterion of its maintained efficiency. I suggest that acceptance trials should take place towards the end of the maintenance period, and after the boiler has steamed about 600 hours since it was last taken off for sooting. Suitable chambers should be incorporated in the design to trap the flue dust, and facilities should be provided for its removal whilst the boiler is on load. Regarding soot-blowing equipment, a considerable amount of research on this type of apparatus is necessary, especially in the direction of stationary elements. All the valves should be operated from one position. As to the American practice of not fitting dumping gear to chain-grate stokers (page 568), my experience in operating this type of stoker shows that this practice is advantageous not only because of the total absence of dumping-gear maintencnce, but also owing to the saving in labour and losses consequent upon the elimination of clinkering. These gains are more than offset, however, by the "carbon in ash" loss. Unless the coal burns very freely, is consistent in grading and quality, and the air distribution is just right, it is impossible to keep an even fire across the grate, and a very high ash-loss results. I should like to ask the author the following questions. (*a*) Has he any experience of burning 15 to 20 per cent volatile coal with archless settings? (*b*) Has the trouble of superheater studs been overcome with the eccentric design of superheater box? (*c*) What is his opinion of the relative merits of plate and tubular air heaters from the operating point of view, especially with regard to the maintenance of a high heat-transfer rate? (*d*) Is any trouble experienced in keeping gilled-tube economizers clean?

Mr. F. Heslop: I note that it is becoming recognized that, in order to prevent "birdnesting," the change in gas velocities leaving the combustion chamber should be gradual. This is accomplished by varying the pitch of the lower boiler tubes so as to form an anti-birdnesting screen. Quite recently I came across a case of birdnesting on marine boilers: samples removed for analysis were found to contain soda ash. This cause is often aggravated by dirty tubes which overheat the tube plates causing slight moisture at the tube ends, which forms a film of soft sodium chloride. On their passage through the tube some of the fly ash or small unburnt particles of carbon adhere to the soft scale, and very soon this accumulates, choking the tubes. Feed water would possibly cause or aggravate birdnesting. With regard to the fuel used in the author's test, I should like to know whether any experiments were carried out with low-volatile Welsh coals, and whether the question of birdnesting has arisen under these conditions. In dealing with "cauliflowering" the author describes a difficulty experienced on chain-grate stokers using preheated air at a temperature of 400 to 500° F. In marine practice it is usual not to exceed an air temperature for combustion of about 350 to 400° F. with mechanical stokers. The word "cauliflowering" is likely to be misunderstood, as in South Wales it is used to describe the opening-up of the coals on burning. This feature is characteristic of Welsh coals when they are being burnt to the best advantage.

Mr. B. L. Price: The inference to be drawn from page 543 and other parts of the paper is that the boiler plant is an isolated unit, and that so long as it transfers a certain fraction of its heat to the steam the potential value of that heat can be disregarded. I contend, however, that the electrical engineer must consider the boiler from the thermodynamic point of view. He must correlate what I would term "calorific efficiency" with its value in the heat cycle; hence also, from a curve of maximum thermodynamic boiler efficiencies at various pressures, the optimum pressure could be decided. I consider that the true basis of comparison between two boiler plants is $\phi(x, y)$, where x = calorific efficiency, and y = value of the heat in the steam cycle. Such functions could be reduced to terms of capital cost.* With regard to the disposition of the plant, the author prefers the economizer and preheater arranged behind—not on top of—the boiler, and he has an open mind upon the question of parallel or perpendicular lay-out of the boilers relative to the turbine house: it seems to me that both these questions, and also that of boiler rating, are factors in the larger question of boiler compactness in relation to turbine plant. Each case must be decided on its own merits. Steam-transmission losses are an important factor in this connection, the variable—other quantities remaining constant—being the length of straight pipe. The absolute value of these losses can be computed in terms of the heat cycle.†

Mr. E. K. Regan: The lay-out of modern steam-raising plants involves the question of what capital expenditure is permissible in order to reach the very high boiler-plant efficiencies now in vogue. It is not generally possible to obtain the overall cost of steam production of such plants, including overhead and maintenance charges, although the fuel cost per unit is sometimes available. More generally, however, the coal consumption per kW is stated: this does not tell us very

* See A. L. MELLANBY and W. KERR: "The Use and Economy of High-Pressure Steam-Plants," *Proceedings of the Institution of Mechanical Engineers*, 1927, vol. 1, p. 53; also K. BAUMANN: "Some Considerations Affecting the Future Development of the Steam Cycle," *ibid.*, 1930, vol. 2, p. 1305.

† F. CARNEGIE: "The Economical Production and Distribution of Steam in Large Factories," *ibid.*, 1930, vol. 1, p. 473.

much. Is it not possible that the attempt to reach higher boiler-plant efficiencies may be offset by the higher capital charges, increased maintenance expenses, and increased power for auxiliaries? The American formula that "if good-quality coal is obtainable at 4 dollars per short ton and the load factor is not 50 per cent, the increase in capital charges may more than offset the gain in high efficiencies resulting from the adoption of the higher pressures" would appear to apply both to the lay-out of the plant and to the working pressure. This question must necessarily be affected by the capital cost per kW of plant installed, which appears to vary from £24 to £12. In reference to this point a specific case can be quoted where the adoption of air heaters (which certainly would have improved the efficiency of the plant by some 2½ to 3 per cent) was found to be inadvisable, as the cost was offset by the capital charges and maintenance charges. As this country generally enjoys a relatively cheap supply of fuel, there must obviously be a limit to which the heat-recovery process can be carried before it actually becomes a loss, as the final figure is the total cost of steam production. The efficiency to be considered, therefore, must necessarily be commercial efficiency. The author's reference to American coal supplies is of interest. It is usual for run-of-mine coal to be supplied, but this is a contentious point as the receiver demands that he should receive the coal already prepared, whilst the supplier argues that preparation for any particular purpose is the responsibility of the user. The reduction of run-of-mine coal to a serviceable condition for stoker firing by means of crushing, adds a further charge to the cost of coal. Coal crushing does not, however, result in a uniformly graded product: it produces approximately 50 per cent fuel of duff size plus anything up to 2 in., depending on the fineness of crushing. Modern coal-preparation methods in use in this country give the coal user a fuel graded to suit the particular purpose for which it is required. In connection with machine-stoker practice, it is found that, owing to uniformity of burning, absence of segregation, etc., a uniformly-sized fuel will give much better results than a fuel from, say, 1½ in. downwards. The author's statement that a correctly-designed boiler plant would eliminate or reduce grit and fly-ash deposits and emission, is very sound. This nuisance appears to be more acute where furnace volume is limited in the endeavour to obtain the highest possible evaporation from the least possible space occupied by a boiler unit. A study of the velocities along the gas track through the boiler would no doubt prove to be very interesting. The use of compressed air for soot-blowing purposes is not new. Prior to the use of fixed soot-blowing elements compressed air was used in place of the old-type steam lance; this, however, was a matter of convenience rather than of economy, as it was found that a compressed-air hose and line was much more readily handled than a hot metallic hose, and consequently tube sweeping was carried out more conscientiously. It is difficult to believe that the National Electric Light Association were able to show a saving of 27·6 per cent in favour of compressed air. I should have thought that steam sweeping would have been cheaper, because the steam is a raw product, whereas compressed air has to be manufactured, at a cost which has to allow for all the motor, main-condenser, and compressor losses. Regarding the difference between American and English stoker practice in the provision of dumping gear, the American figures for combustible-in-ash loss are not so good as those generally obtained in this country. From observation of American-type stokers operating in this country it would appear that—although dumping irons are not fitted—the last few feet of the chain grate are inoperative from a combustion point of view, and an additional area of grate has to be purchased to complete the burning down, whereas on the British system the whole of the grate area is actively employed and the ash works its way over the dumping irons. The maintenance cost of dumping irons, given a reasonable design, is not formidable, and at least 2 years' service can be obtained from a set before renewals are necessary. The author's experience with preheated air, and the effect of the latter on certain coals, form the most interesting part of the paper. It has been customary, for want of a better term, to describe the opening-out characteristic of Welsh coals as "cauliflowering." In view of the author's experience with other coals and his definition of "cauliflowering," this expression does not appear to be correct when applied to Welsh coals. The opening-out characteristic of Welsh coals is a valuable asset, as, contrary to the experience of the author with other coals, it has the effect of aerating the fuel bed and rendering it extremely porous; whereas the phenomenon described by him has a directly opposite effect.

Mr. J. S. Evenden: An important practical advantage of pulverized-fuel firing which is not mentioned by the author is the ability to cut off instantaneously the source of heat supply to the furnace. This is a valuable feature in case of emergency, particularly with large units. In regard to damage to superheater elements during steam raising, this is likely to occur in either the single-pass or multi-pass arrangement unless steam is passing through the tubes, and the author's proposed method of supplying this steam from a saturated bus-line and returning it to the main superheated-steam range is of particular interest. In regard to superheater-element supports, the author will perhaps agree that there are now available heat-resisting steels which have proved thoroughly satisfactory for this purpose, and it is therefore scarcely necessary to go to the length of devising air-cooled supports.

Mr. C. G. Morley New (*communicated*): The author appears to have a bias in favour of pulverized-fuel firing, at least for large boiler units. I should be interested to know the lower limit of size which he places to the advantage of pulverized fuel over mechanical stokers. He states that pulverized-fuel firing is temporarily out of favour, a fact at which one cannot be surprised, seeing that at first great stress was laid on the fact that it could be used for low-grade fuels, and that no trouble could possibly arise from dust. We now find that good and consistent fuel is necessary for first-class performance, and that the dust problem can only be solved by additional costly equipment. I agree with the author when he states on page 546 that what really matters is the overall cost of steam production. We hear quite a lot nowadays about thermal efficiency, but very little

about the total cost of production, including the large item for capital charges. Under the national scheme, however, we shall shortly hear more about the total cost of generation. With regard to the efficiency of 90·47 per cent given in Table 3, it would be interesting if the equivalent power absorbed by auxiliaries were deducted in order to compare this with the net boiler efficiencies given for a stoker-fired installation in Table 5. I should be glad to have the author's views on the subject of pulverized-fuel firing with the low-volatile coals we have available in quantity in this area, where the problem is to burn efficiently coals with 10 to 12 per cent of volatiles.

[The author's reply to this discussion will be found on page 601.]

East Midland Sub-Centre, at Loughborough, 22nd March, 1932.

Mr. F. H. Pooles: The paper proves conclusively that powdered-fuel firing on modern lines is more reliable, more efficient, and easier to handle, than other types of stoking, whilst its cost is comparable with those of other types. There has been a great deal of progress in the last 5 years in the design and lay-out of powdered-fuel plant, and there are now very few engineers who would voluntarily go back to stoker plant after they had had experience of powdered-fuel firing. I do not support the author in his preference for the bin-and-feeder system. Why does he think it necessary to store powdered fuel? In my opinion the unit system is far in advance of the bin-and-feeder system. For large boilers having several milling units, there is certainly no necessity for the storage of powdered fuel. By omitting from the plant any provision for storage of fuel we can considerably reduce the maintenance charges, owing to the absence of air and coal lines, cyclones, screw conveyors, etc. Operating labour is also reduced to a minimum in this way, whilst the design of the boiler house is simplified. The unit system is quite as efficient as the old-fashioned bin-and-feeder system. Regarding the rate of evaporation per square foot of heating surface, the author's figure of 5·5 lb. per sq. ft. per hour is very conservative. Figures of 20 lb. per sq. ft. per hour for normal running and a maximum of 30 lb. per sq. ft. per hour for overload rating are being obtained daily in a central station not far from here, without excessive gas speeds. Referring to Table 12, the author seems to have been unfortunate in regard to his experience with the superheaters installed at his station. Superheaters of the same type of which I have had experience have given no trouble except for slight burning of the supports, and this was remedied by the use of a better class of heat-resisting metal. It is interesting to find that the milling plant operated satisfactorily. Could a stoker-fired station show similar results? Brickwork seems to be the most fruitful cause of boiler outages. In this connection the ideal to aim at is to keep all refractory material away from the action of the intense heat, and, if possible, to design the combustion chambers in such a way that they are completely covered with water tubes. My experience has been that spaced-tube construction gives the best all-round results and the least trouble. It is less expensive to install than other types of water-cooled combustion chambers, and it will deal with any type of fuel likely to be met with in this country. The author's method of protecting the superheaters during the period of pressure-raising is ingenious, but unless some system is adopted to ensure that one of the valves on the steam drum is not inadvertently left in the closed position, there is a danger of burning out the superheater. I agree with the author's contention that most of the dust-emission trouble can be eliminated. If in the design of the boiler special attention is given to the speed of the gas, a large proportion of the dust can be deposited before it reaches the dust catchers.

Mr. W. Warren: I should be glad if the author would state the working pressure of Boiler No. 15, which is variously given as 375, 398, 380, and 373 lb. per sq. in. in different parts of the paper. Mention is made of a device for extracting the pyrites from the coal at the mill. I do not understand why in the first test 7 351 lb. of pyrites were extracted from the mill, whereas in the second test—over a similar period—705 lb. were extracted from coal of higher sulphur content. The figure of 3·3 per cent given for the total moisture content of the coal is very low. If, as is stated, the coal left the mill at the high temperature of 143° F., I think that, with a total moisture content of only 3·3 per cent, some of the lighter hydrocarbons would be driven off. The test figure for combustible in the ash (less than 1·0 per cent) is particularly good for a pulverized-fuel-fired unit over a period of 100 hours. No mention is made, however, of how and where the ash is collected.

Mr. F. Dransfield: The station with which I am connected has similar milling equipment to that described by the author, and we have the additional difficulty of very poor coal (about 9 000 B.Th.U./lb.) to contend with. Will the author give further particulars of the alterations to the mills and ducting which he has found to be effectual? We cannot reduce our consumption below 15 to 16 kWh per ton, at a fineness of 80 per cent through a 100 I.M.M. mesh. I am in agreement with the author's remarks about the necessity for a radical change in the design of superheaters. Our boilers are fitted with superheaters of the type he describes, except that they are placed between the boiler tubes, the boilers being of the semi-vertical type. At first we did not get the required superheat temperature of 800° F., but by pushing the superheater forward until the front legs are directly exposed to the furnace, and are virtually functioning as a radiant superheater, we have reached that figure. This is not a desirable way of overcoming the difficulty, as although the tubes are standing up to the conditions they are sagging slightly between the supports. Ordinary heat-resisting steels have not proved suitable for these supports, but Hadfield's "Era" steel is proving satisfactory. The original mistake lay in adopting the inter-tube type of design for the superheater. I think that the boiler tubes had a cooling effect on the superheater, since they were only about 1 inch away from it. Superheaters should be put into a special chamber of the boiler, where they are not cooled by the

boiler tubes, and where there is some control over either the temperature or the quantity of gas circulating round them. An inter-tube superheater increases the tendency to slagging or " birdnesting " in the first pass of the boiler. We have not had very satisfactory experience with an air heater of the parallel-plate type, possibly because this particular heater is rather heavily rated. With more conservative ratings the type should be successful. The Ljungström air-heater is especially suitable for pulverized-fuel working, as it is practically self-cleaning. Our experience of this device has been very happy. Soot-blowing by air appears to offer advantages over steam soot-blowing, particularly in conserving valuable distilled water, and in preventing condensation in the later stages of the boiler unit. We are operating with automatic control, an essential feature if one is to take full advantage of the controllability of pulverized-fuel boilers. The variable-speed commutator motors used for the main fans have run for over two years without trouble. Their high power factor is an advantage, and owing to the excellent control and the fact that the fans run most of the time below their maximum speed, they are very suitable for this work. Auxiliary consumption on low loads is therefore very low. Fan wear, one of the boiler-house engineer's most recent troubles, is aggravated by constant fan speed and damper control. A variable-speed motor or gear on a fan will reduce fan wear considerably. Designers should concentrate on reducing the necessity for taking boilers out of service for cleaning. One cleaning a year should be sufficient; as units grow in size the necessity for continuous availability will increase. Proper water control has made it possible to do without internal cleaning for longer periods than this: it now remains to overcome the slagging and wall-erosion difficulty. Our experience with preheated air on chain-grate stokers has been similar to that of the author. Where the hot air passes through both forward and return parts of the chain, there is no difficulty up to 350° F. Where the stoker is so designed that the air passes through the upper part of the chain only, hot air—even at 150° F.—cannot be used, and as the grate enters below the coal hopper its temperature reaches 500° F. As a result the layer of coal in immediate contact with it becomes carbonized, and we get coking or " cauliflowering."

Mr. D. H. Brown: I should like to refer first to the author's prophecy that the retort-type stoker is likely to come to the fore as an alternative to pulverized fuel. I can best express my objections to the use of this type of stoker by quoting the remark (page 566): " No moving parts, driven either from the moving grate surface or by external means, should be employed for the removal of riddlings or fines. These can be removed without such risk-engendering complications." The rods and spindles in the air box of a retort-type stoker are likely to cause trouble when they are acted upon by the riddlings and fines, and in my view the plant installed should be capable of being maintained at the lowest possible cost. One retort stoker I saw some years ago was in such a bad state that about 25 per cent of the total fuel fired found its way into the air chamber below. It was therefore necessary to stop the stoker every 2 hours and remove this coal. While the retort-type stoker is efficient when maintained in good condition, and can take up the load very quickly, its banking losses appear to be much higher than those associated with a chain-grate stoker. Although the author indicates that it would be advantageous to install electrical equipment for stoker drives, he complains about the first cost. A variable-speed (or commutator-type) motor costs about 150 per cent more than a slip-ring motor, but when the price of the gear box is added to that of the slip-ring motor the difference between the costs of the two systems is not too much, considering the extra efficiency gained by the better control of the stoker speeds. Turning to the author's figure of 5·5 lb. per hour per sq. ft. of heating surface for the average evaporation, I suggest that it is quite safe to work at about 7 lb. per hour per sq. ft. I am doubtful as to the safety of higher figures, except, of course, in the case of steam generators. As to the suggestion that 35 lb. per hour per sq. ft. of grate area is a reasonable combustion rate, a very efficient Lancashire station is at present working at about 22 to 23 lb. per hour per sq. ft. Would the author state what he considers to be a reasonable figure for a plant working without preheated air? Mr. Dransfield referred to air heaters, and I note that the author recommends that these should have no moving parts. My own experience of both types of air heaters makes me disagree with the author on this point: I should choose an air heater of the Ljungström type.

Mr. S. J. Allwood: I should like to ask the author at what load factor the pulverized-fuel plant referred to on page 550 is operating. Also, what is the load factor of the Deptford West (stoker-fired) station? With regard to the evaporation rating of the boilers, my experience to a great extent supports the author's remarks, and, considering the cost of steam production in conjunction with thermal efficiency, I think the figure of 5·5 lb. per hour per sq. ft. is a reasonable one. Turning to combustion-space design, what heat-release figure does he suggest for stoker-fired plant? In my opinion 35 000 B.Th.U. per cub. ft. is a reasonable figure. With reference to the question of reliability of plant, my attention has been called to a plant with stoker-fired boiler which has operated for the maximum period allowed by the Home Office—14 months—without coming out of service. This demonstrates that in this respect mechanical stokers are in no way behind pulverized fuel. I have three examples of this class of boiler which have been running for 4 years, and we have never yet taken one of these boilers off the line owing to a stoker failure. Referring to the figures of maintenance cost, 19·5d. per ton for the pulverized-fuel plant is justified, considering that the figures are now somewhat lower. However, I can show a figure of 10·2d. per ton for a stoker-operated boiler, which compares well with the figures for the stoker-fired plant dealt with in Table 11. The stoker maintenance for that plant costs 5·45d. per ton, compared with 1·72d. per ton for the stoker plant I have in mind. The stoker-operated plant of Table 11, therefore, is perhaps not the best to judge by. The author states that chain grates are uneconomical in first cost for boilers rated at more than 200 000 lb. per hour; what would be the comparative figure for the

bin-and-feeder system to which he refers? I should be glad of an explanation of the very large variation shown in the coal-preparation costs of Table 15. Is it necessary to choose the fuel to be employed for powdered-fuel firing? Almost any kind of fuel can be burnt on a stoker. The maintenance cost of retort-type stokers is somewhat prohibitive, and they do not readily burn a fuel with a low volatile content. On the other hand, they are very flexible in operation, control is maintained over the whole of the fuel bed, and an arch or suspended roof is not required.

Mr. L. M. Jockel: The essential characteristics of modern boiler plant are low cost and high commercial efficiency. I am inclined to think that in the past thermal efficiency has been made something of a fetish. Referring to page 546, the efficiency equation given really takes into account the commercial aspect of the question, as distinct from the thermal efficiency of the boiler units. I should like to point out that the maintenance figures for the Hams Hall station (page 522) are hardly comparable with those for other plants, as this station only came into operation comparatively recently. The maintenance cost for furnace brickwork given in Table 11 is very high; I suggest that it should not exceed 3d. per ton. I know of one or two plants which are aiming at a figure of 1d. per ton of coal burnt. On the same page the author discusses the question of reliability, and refers to the fact that lack of attention to detail in design or construction is often the cause of unreliable operation. In this connection I should like to say that in many cases the trouble has arisen through lack of co-operation between the people who design and make the plant, and those who have to operate it. Does the author regard as desirable a heat-transmission rate of 100 B.Th.U. per min. per sq. ft. of boiler heating surface, and would he favour a heat liberation of 5 000 B.Th.U. per min. per sq. ft. of grate area for mechanical stokers? As to the period of test, would any experienced engineer agree to anything below 8 to 10 hours? In my opinion a 24-hour test period is desirable. On page 558 there appears a surprising statement to the effect that no special apparatus for grit extraction should be necessary, and I should welcome further information in support of this view. I am particularly interested in the author's reference to the inefficiency of the average steam-blower, as I have for some years advocated the use of compressed air. I suggest that soot blowers should be machine-operated and not hand-operated, in order to avoid staccato action. With regard to superheaters, has the author had any experience with independently-fired units? My experience of independent superheaters has been a happy one, and it would appear that a case could often be made out for having a percentage of independently-fired superheater units along with integral units in a power station. I should like to ask the author for his views on the possibility of doing away with air-heater ducts (page 568) and utilizing a heat carrier in pipes, which would convey heat from the heating unit and transmit it to a receiver unit. Some nine years ago I was engaged upon pioneer work in connection with the regenerative type of preheater when it was first introduced into this country. My experiments dealt with air at temperatures between 400° and 500° F., but I agree with the author that a temperature of from 300° to 350° F. is the optimum figure for mechanical-stoker plant. With regard to the lay-out of boiler plant, I should like to emphasize the importance of cranes or runways for lifting heavy parts of the gear over the tops of boilers. No permanent provision is usually made for this in boiler houses, and temporary tackle has generally to be rigged up for carrying out repair work. The slight extra capital cost of permanent lifting equipment is repaid in a few years of operation.

Mr. R. H. Gummer: The outstanding feature of the paper is the vindication of the claim made by the designers of pulverized-fuel firing equipment with regard to operating reliability. The information given in the paper tends to confirm the prediction that the plant of the future will have pulverized-fuel boiler units of from 500 000 lb. per hour capacity upwards, housed in one building with the turbine unit under the supervision of an individual operator, the plant being controlled automatically. The paper is incomplete in that the author omits to state what he really thinks is the best type of boiler plant to install. With regard to the permissible evaporation per square foot of heating surface, as Table 12 contains no record of the loss of even a single hour's steaming on account of tube failure, although the tubes in question regularly evaporate 25 to 30 lb. of steam per hour per sq. ft. of heating surface, I should like to ask how the author arrives at such a low figure as $5\frac{1}{2}$ lb. per hour per sq. ft. of heating surface for his ideal design. Another point associated with Table 12 is that of boiler outages. The fact that most of these are due to causes in no way connected with the pulverized-fuel machinery or equipment, suggests that we are approaching the ideal of continuous service, i.e. of having a boiler unit continuously on the line from the period of one boiler survey to the next. I should like to ask the author for his observations on this feature. With regard to the important part of the paper dealing with dust emission, little reference is made to the cyclone dust-eliminating equipment installed on the large pulverized-fuel plant at Barking, and I should therefore welcome information as to its efficiency and any special difficulties encountered in connection with it.

Mr. J. F. Peck: The difficulty of maintaining the fineness of the pulverized coal with the crushing roller type of pulverizer also affects the high-speed impact and attrition mill commonly used in this country. As the pegs of this device become worn, the coal gets coarser. It appears that we have overlooked the good qualities of the ball or tube mills with air separation, which maintain a uniform fineness over long periods. Troubles due to wear are overcome by adding more steel balls while the equipment is running, and the maintenance charges of this type of mill are low. The greater degree of fineness made possible by the ball type of mill results in more rapid and complete combustion, a shorter flame, and less slagging. One large American station using these mills reports a consumption of about 10 kWh per ton of coal, although the coal is ground much finer than in this country. It appears to me that by using an efficient regenerative air heater one could dispense with the economizer, the feed heating being carried out more

economically by stage bleeding. This would improve the overall efficiency of the plant, and the boiler plant would be simplified. The high preheater temperature favours the complete water-walled furnace and the combustion of low-grade fuels. Regarding boiler ratings, I have had some experience of Naval boilers in which evaporations of 20 to 25 lb. of water per sq. ft. of heating surface per hour are common. Compressed air for soot blowers has been used in the Navy for many years, because of the loss of water associated with the steam-jet type.

Mr. F. Nicholls: The figure of 75 per cent for boiler-plant efficiency, which represented first-class practice in 1924, had shown no material increase for a period of some 20 years prior to that time. It may therefore be claimed that the advent of pulverized-fuel firing, and the stimulus applied in consequence to all forms of firing equipment, have effected an increase in efficiency of at least 10 per cent in the short period of 6 years. The plant which the author has operated appears to be very similar to our own, and his experiences seem to go hand in hand with ours. Regarding the troubles which he has experienced with his pulverized-fuel-fired boilers, I note that he attributes the major proportion to refractory-lined combustion chambers. It must be borne in mind, however, that in consequence of the recent large increase in the size of steam-raising units, refractory troubles are not confined to pulverized-fuel-fired units. The increase in the size of combustion chamber, together with the more severe conditions imposed by increased evaporative ratings, render these troubles inevitable with any type of firing equipment. The evolution of the all-steel tube combustion chamber, in conjunction with the modifications in the dispensation of the heating surface, has, however, now reduced these troubles to the point of almost entire elimination so far as pulverized-fuel firing is concerned, and in this direction it would appear that the only restriction imposed on the size of units for this system of firing are of a manufacturing nature. So far as stoker equipment is concerned, it would appear that the breakdown hazard will increase in direct proportion to the size.

Additional Communication to the Discussion.

Mr. E. L. Damant (*Natal; communicated*): The author appears to be very favourably impressed with pulverized-fuel firing for steam-raising purposes, but makes little mention of the disadvantages, which are now well known. The cost of milling is quoted in several instances, but this varies within such wide limits, viz. 6 cents per ton to 66·9 cents per ton (neglecting the cost of electrical energy) in America, that it appears to be impossible to draw any conclusions from the figures quoted. The author's estimated cost of 3d. per ton on page 575 presumably excludes the cost of electrical energy, but, even so, it is an extremely low figure. This figure will naturally depend upon the daily output of the mills, and, in comparing the cost with those obtaining in other countries, it is necessary to know the cost of the major items of renewal, such as the bull ring and the rollers. I should be glad if the author would supply these figures. I have experienced much the same troubles with the Raymond mills and have solved them in a very similar manner. A life of 20 000 tons from a bull ring is easily possible, and I expect to increase it shortly. The fineness of the coal produced is such that 95 per cent will pass through 100 mesh (Tyler standard). These mills have a rated capacity of 6 tons per hour and the results obtained therefore compare very favourably with those from the 15-ton mills quoted by the author, viz. 40 000 tons per ring. Dust-extraction processes are now sufficiently efficient, so that the possibility of trouble due to this cause is remote. The cost of these processes for capital, operation, and maintenance, must, however, be appreciable and will vary very considerably, depending on circumstances. I have not seen figures of cost for this work and it would be interesting if some could be supplied. Once the ash or dust is extracted the disposal is by no means a simple matter; here, again, information on the subject would be of considerable value. Against these costs, however, we have the saving in stoker maintenance and furnace-brickwork maintenance. The latter item is quite appreciable in the older types of pulverized-fuel furnaces where the "fraction cold" amounts to from 0·5 to 0·75. In the newer types, however, where the fraction cold is practically 100 per cent, this item of cost has been almost eliminated. Flexibility in operation is a very real advantage, but the saving in standby or banking losses is not so great as is generally assumed. Lighting-up losses are considerable and might offset the gain during banking periods. It must be remembered that during pressure-raising periods combustion is extremely inefficient and that if a standby boiler is continually being brought up to pressure a serious loss might result. The test results shown in Tables 2 and 3 respectively are interesting. The heat balance in Table 2 shows a loss due to combustible in the ash of 1·32 per cent, which is a very good figure for that type of burner and furnace. The corresponding figure in Table 3, however, shows a heat loss of only 0·22 per cent. This figure is exceptionally low and has not, I think, been equalled anywhere for similar boiler plant. The author does not state the degree of fineness of the fuel that was used in the two tests, nor does he state what modifications, if any, were made to procure such an excellent improvement in combustion. I should be glad to know how this loss was measured in the tests, and by what means the improvement was effected. Although the author states that the energy consumed by the auxiliaries should be debited against the boilers, this has not been done in the tests under discussion, and in this respect the energy consumed by the auxiliaries in the coal-preparation plant should also be debited against the boiler house if any comparison is being made with the results from stoker-firing. The results in Tables 3 and 5 are, as the author states, not comparable, but their close proximity in the paper inclines the reader to make a comparison, and, indeed, it seems almost impossible to compare the efficiencies of the two methods of firing because all the items of loss in the heat balance-sheet depend either upon the quality of the coal (moisture, ash, etc.) or upon the size of the heating surfaces of the

air heater and economizer (uptake losses) or the size of stoker and furnace volume (combustible-in-ash loss). The only possible comparison is that of two similar plants of equal capital cost burning the same quality of coal, and it is almost impossible to obtain such a comparison. With regard to the low loss reported in Table 3, it appears that the heat liberation of 16 000 B.Th.U. per unit furnace volume is about equal to that obtaining in other plants of similar furnace and burner design, but Fig. 3 seems to indicate that the furnace is not of similar dimensions to those of which I have knowledge. It is apparent that combustion will depend upon the relations between the width, length, and height of the furnace, and I should be glad if the author could furnish these dimensions as well as the distance of the centre line of the burners from the front wall. I heartily concur with him that far too little attention has been paid by designers to the question of the control of boilers. It might be accepted as an axiom that the more accessible and flexible the control the greater is the efficiency in operation. Frequently the services of an additional operator might be dispensed with, and a little capital expended on controls will give a remunerative return.

The Author's Reply to the Discussions at London, Manchester, Liverpool, Cardiff, and Loughborough.

Mr. J. Bruce (*in reply*): In the first place I have to thank the many speakers who have supplied, in addition to constructive criticism, statistics and data which form a valuable supplement to the paper.

The points raised in the discussions were many and varied, and where it has been impossible to reply collectively I have done so individually.

The point which appears to have aroused the greatest controversy is in the suggested rating per square foot of evaporative heating surface. I feel that the views expressed in the paper on this subject have not been fully understood. When I suggest that the normal rating should be 5·5 lb. of water per square foot per hour of evaporative heating surface I refer distinctly to the older and usually-accepted form of boiler design; e.g. the sectional water-tube type. My remarks do not apply to boiler units of modern design which have entirely broken away from old and accepted practice. Examples of this modern type are the Wood steam-generator and the recently-introduced Johnson boiler. I agree that this latter type of steam generating unit can be designed for very much higher rates of evaporation.

Mr. Gaze does not agree with my suggested rating for the older types of design, and says that such a figure is very unlikely to be generally adopted. I would point out that in the recently-constructed Clarence Dock station at Liverpool the boiler plant has been designed for this figure at normal rating. Further, the boiler plant in the new Barking "B" station has a similar design figure, and Mr. Gaze will find that many other modern capital stations operate in the neighbourhood of the figure I mentioned. The argument I advanced in the paper was against any undue increase of this figure for the old types of design.

Another point raised by numerous speakers, particularly Mr. Townley and Mr. Nichols Moore, was the fact that no reference is made nor are statistics given in the paper relative to capital costs. When the paper was first projected serious consideration was given to the question of capital costs, but it was found extremely difficult to put forward figures that would have been of any value. Capital costs relative to the various stations discussed are not of much use, owing to the fact that the plants have been designed at different times and the costs do not bear the same relation to each other. Further, it was found that examples of capital costs for the illustration of a technical paper were a different matter altogether from capital costs with the possibility of a contract behind them!

A considerable proportion of the discussion is devoted to the vexed question of the relative merits of equipping boiler plant with pulverized-fuel firing or mechanical stokers. I think the paper fully expressed my views on this subject, and while I realize that the modern retort stoker is a serious competitor of pulverized-fuel plant for the large boiler unit I am sure—from what I have seen of retort stoker equipment—that it is a much more complicated assembly of moving parts than even a bin-and-feeder pulverized-fuel plant. Consequently the retort stoker equipment is much more liable to break down.

In connection with pulverized-fuel equipment, the discussion has also been productive of much argument as to the merits of the unit and the so-called bin-and feeder systems. Here, again, I have stated my views on this subject fairly fully in the paper but I want it to be clearly understood that while I favour the bin-and-feeder system I am not referring to the existing examples of that type of pulverized-fuel equipment at present in operation in this country. I feel that even the best combination of boiler plant designed for a unit system would be greatly protected from outages by the incorporation of a modified bin and feeder.

The question of the efficiency attainable with stoker and pulverized-fuel combustion equipment has been raised by various speakers. I agree that with either system of firing and for short periods—such as tests—there is nothing, as far as thermal efficiency is concerned, in favour of either system, but over long periods of operation a higher sustained thermal efficiency is obtainable with correctly designed and applied pulverized-fuel plant. In addition there are the further operating advantages set out in the paper.

Regarding the problem of refractories, this is so intimately dependent upon the whole combustion-chamber design that it cannot be considered as a separate item. The ideal arrangement points to the entire elimination of refractory. This is accomplished in one design of boiler unit, and is in successful operation with pulverized-fuel and high preheated air temperatures. Where a degree of refractory is necessary—such as with stoker-equipped water-cooled combustion chambers—

I agree that the block-covered tube, such as the Bailey type, offers an admirable solution, but there are many engineers—particularly in America—who show equal preference for the use of the fin tube or even the plain tube.

In reply to Mr. Clinch, I am aware that recent power-station installations have included plant in which the number of boiler units per turbine unit is as suggested in the paper. These plants, however, are not of great capacity, as they employ comparatively small turbine and boiler units. In the paper I was referring more to the large stations of the future. I am surprised that Mr. Clinch has not fully understood and appreciated the suggested formula for the calculation of boiler *house* efficiency. From his remarks it is evident that he is under the impression that the calculation of boiler *plant* efficiency is all that is required. Surely he is aware that in the processes of steam generation many losses can occur in addition to those peculiar to the combustion cycle and the boiler units themselves. Mr. Clinch stresses the importance of the variable losses. What, then, can be more variable due to mal-operation—in spite of good design—than range, drain and blow-down losses? The suggested formula enables these losses to be readily checked. Mr. Clinch criticizes the lay-out of the boiler plant in Fig. 3. This was included in the paper to illustrate those sections dealing with the station with which I am associated, and was not put forward in support of my opinion of the method of application of pulverized-fuel firing.

Referring to boiler plant outage, and presumably to page 552, which shows that no outages were caused as a result of the failure of the coal-preparation plant, Mr. Clinch says that such a result is not due to any merit of pulverized fuel, but merely to the group system. (Presumably Mr. Clinch is referring to the interconnection of the powdered-fuel bins.) I cannot follow his reasoning here, for since only a pulverized-fuel system is used on this boiler plant, how can the credit for the results be ascribed to anything else? Certainly the major portion of the credit must go to the design and arrangement of the coal-preparation plant. However, after Mr. Clinch places the credit for the results to what he terms the group system—a feature which can only be incorporated with a bin-and-feeder arrangement—he goes on to say that he, *therefore*, considers that unit systems should be adopted! The one disadvantage of the bin-and-feeder system cited by Mr. Clinch has not been met with in my experience, and it should certainly never arise unless a full bin of fuel is allowed to stand for weeks. When a boiler unit is going out of service for any length of time the fuel bin should be emptied during the final steaming hours.

I do not agree with Mr. Clinch's remarks on reliability.

In connection with soot-blowing, and Mr. Clinch's views thereon, I can assure him that it is quite possible so to design a boiler unit that during soot-blowing periods the chimney emission will not contravene the usual ordinances.

I have already dealt with the points raised by Mr. Gaze relative to rating per square foot. He is of the opinion that the boiler unit of the future will be of the superimposed type rather than, what he terms, the "bungalow" type. I agree with him that where land is expensive the former type of unit will be forced upon boiler designers, but, more than that, the whole design of the station has to suffer also. I am firmly convinced, however, that there is no need for generating stations to be built in urban or suburban areas, and cheap sites can be found where the amenities of the neighbourhood will not be interfered with.

The statistics given by Mr. Gaze relative to the stations of the London Power Co. are extremely interesting, but I feel that his development of high ratings on old designs of boiler units has been forced upon him because of the expensive sites on which the stations are built, and in my opinion it is not a practice which will be widely copied in the design of new stations.

The data given by Mr. Highfield relative to generating stations supplying Paris are valuable and interesting, especially in view of the fact that last year I had the privilege of visiting some of the stations mentioned. I feel that the design at Vitry South station could have been very much improved upon, particularly in regard to the lay-out and arrangement of the boiler-house plant.

I am glad to find Mr. Lunn in agreement with me on so many points, but I disagree with his view that the retort type of stoker will be extensively used in this country for some time to come.

I regret that the paper contained such scanty details of the effect of high temperature on such parts as steam-range joints, bolts, superheater tubes, safety valves, and safety-valve springs, but I have met very little trouble due to high temperature on these components.

In connection with boiler-water concentration, I hold the view that the average modern figure should not exceed 150 grains per gallon. Preferably it should be maintained not higher than 100 grains per gallon.

I am pleased to note that Mr. Adams agrees with me on many points, particularly with regard to the rating of modern boiler plant. He raises the question as to why, on the extensions to the station with which I am associated, stoker-fired boiler plant has been adopted. I would point out, however, that when these extensions were contemplated some years ago our experience with pulverized-fuel firing had, at that time, been very short.

In reply to Mr. Russell, I regret that I am unable to suggest any better remedies for economizer troubles than those which have already been mentioned. In connection with the use of inert gas, or rather, returned flue gas, for combustion control, I have had considerable experience of this. The adoption of such a system, however, necessitates careful jointing and caulking of the ducting and stoker casing construction, since leakage can cause considerable difficulty in operation due to the presence of sulphur fumes in the neighbourhood of the operating floor.

Replying to Mr. Hamilton, I am not aware of any plant of reasonably large capacity equipped with stokers operating at 70 lb. to 80 lb. of coal per square foot of grate area, but one or two individual boiler units have been operated for short periods of a few hours at these combustion rates, pointing to the fact that these rates can be attained. Whether such plant can be designed to operate over long periods of service and at an economic cost remains to be seen.

In connection with outage periods, boiler-plant availability, etc., I have to thank Mr. Hamilton for correcting the item, "total hours boiler unit was available for service," under Boiler unit No. 22, in Table 12. I agree that it should be possible to complete the annual survey and overhaul of the modern boiler unit in approximately a fortnight, and I also agree that in the calculation of a factor expressing on a comparable basis the availability of a boiler unit it would be preferable to use a common denominator such as Mr. Hamilton suggests.

The rate of evaporation which I have suggested as the normal rating per square foot of evaporative heating surface for the commonly accepted form of boiler unit has been criticized by one or two speakers, but, on the other hand, it is supported by Mr. Hamilton, and it is of considerable interest to know that the Clarence Dock boiler units have this design figure for normal duty.

Referring to damper controls and the point raised by Mr. Midgley about the location of wire cables for damper operation, I do not mean that these should be so placed as to be out of sight and out of mind, but rather that they should be carried where they do not intrude or are not unsightly. Too often the appearance of the casing of a boiler unit is spoilt by a collection of damper operating cables and spindle extensions from valves.

Mr. Midgley favours the arrangement of combustion equipment which provides for base or normal-load operation on stokers, with pulverized-fuel boosting to meet overload and sudden steam demands. Why, however, complicate the firing arrangements by installing two distinct types of equipment when equal flexibility can be obtained at possibly a lower total cost by pulverized-fuel equipment alone?

I do not entirely agree with Mr. Pausey in his remarks relative to the water-wall construction of combustion chambers. A tube, sloped as suggested in the paper, will give a freer release to the generated steam than a vertical tube or one which slopes inwards at the top, but I agree that in any design free circulation is the first necessity.

It has been my experience that if scale-forming salts are allowed to enter the boiler water—even if present in only small quantities—these salts will precipitate and concentrate on the hot spots of wall tubes, and blistering and eventual puncture will result. I have found this even with a deposition of scale as small as 1 sq. in. and approximately $\frac{1}{16}$ in. to $\frac{1}{8}$ in. thick.

The points raised by Mr. Nichols Moore relative to capital charges and the Barking extensions have already been dealt with in my reply to other speakers. He is under a wrong impression in considering that the paper is of value principally to operating engineers. I would further point out to him that those most competent to form a considered opinion of generating plant performance and also to specify and install such plant are station engineers.

Mr. Nichols Moore is emphatic in his conclusion that considered opinion in this country indicates a preference for stoker-fired boiler plant. Those who have taken part in the discussion and have had actual experience of modern pulverized-fuel plant, however, are of a different opinion.

In Table 10, referring to the operating costs of the Hams Hall boiler plant, the item for furnace brickwork was not included because I understand that, at the time, the furnace brickwork was still in the contractor's hands.

In connection with Table 11, the statistics given cover the last three years' operation, and the overall figure of 79·41 per cent for the stoker-fired plant, which has been in existence for 10 years, is very creditable. It must be understood that this figure is the *overall* boiler-house efficiency and not merely the boiler-plant efficiency, which so many engineers wrongly consider to be the true figure for comparisons.

In reply to Mr. Reeman, I agree that, strictly speaking, the performance of the modern boiler unit is not comparable with that of the turbo-alternator, but I do not think that the difference of comparison should make such a discrepancy between the reliability of the turbo-alternator and the boiler unit. Surely, in the case of the boiler unit, it rather points to the elimination of all risk of mechanical failure and the training of the human element which is to be used for operation.

Replying to Mr. Burr, in connection with the fineness of the product for pulverized-fuel firing, I feel that at least 75·00 per cent through a 200 I.M.M. screen is desirable, and that no residue, or not more than 0·5 per cent, should be left on a 40 I.M.M. screen.

In connection with the latter part of Mr. Hill's remarks:—

(*a*) I have had no experience of burning 15 to 20 per cent volatile coal with archless settings.

(*b*) No trouble with superheater studs has been experienced with the eccentric design of superheater header.

(*c*) The plate type air-heater is very much superior to the tubular type from all points of view, and particularly with regard to high heat-transfer rates.

(*d*) No trouble is experienced in keeping gilled-tube type economizers clean.

In reply to Mr. Morley New, it is difficult to place a limit of size to the boiler units which should be equipped with stoker plant and those which should be equipped with pulverized-fuel plant. My personal view is that up to 200 000 to 300 000 lb. per hour capacity the stoker is a serious rival to pulverized-fuel equipment, particularly in the lower ranges of capacity, but for units above the range of output mentioned I am quite convinced that the merits of pulverized-fuel plant preclude the use of any other form of combustion equipment.

I have had no experience in the burning of low-volatile coals with pulverized-fuel plant, but I have successfully burnt Welsh bituminous nutty slack with the following approximate analysis:—

	Percentage on sample "as fired"	Percentage on sample "as dried"
Moisture	4·36	—
Volatile matter	20·48	21·40
Fixed carbon	59·98	62·70
Ash	15·18	15·90
	100·00	100·00
Sulphur	1·58	1·65
Calorific value, B.Th.U. ..	12 400	12 940

This, however, cannot be classed as a low-volatile fuel.

In reply to Mr. Warren, with reference to the test figures and other data given in the paper relative to No. 15 boiler unit, the various pressures tabulated are due to the fact that the disposition of the steaming turbine plant may necessitate a boiler unit supplying steam through a lengthy range. Actually the operating pressure of the boiler is 375 lb. per square inch (gauge). The large difference in the reported weights of pyrites extracted from the mill of this boiler unit during these tests is entirely due to the fact that two very distinct and different coals were burnt—the one high in iron pyrites and the other very low, even though, in the case of the latter, the total sulphur content was high.

In connection with the mill outlet temperature referred to by Mr. Warren, I think that 143° F. is not unduly high, even considering the amount of drying which is effected. No difficulties due to temperature of drying gas have been met with in mill operation.

In reply to Mr. Brown, I think that a reasonable combustion-rate figure for chain grates operating on cold air is from 25 to 30 lb. per square foot of grate per hour.

In reply to Mr. Allwood, it is not necessary to choose particularly the fuel to be consumed for pulverized-fuel firing. The contrary impression is one that quite a few engineers seem to have obtained, and I do not think they could have gained that impression from anyone operating a modern pulverized-fuel plant. Such plant will burn without trouble a wider variety and grading of coals than any type of stoker equipment. In the case of the station with which I am associated, we have had wide and frequent changes in the coal supply to our pulverized-fuel plant during the course of even one day, but it has been so unnoticeable and the effect on the plant has been so small that the operating staff has not been aware of any change in fuel quality.

In reply to Mr. Jockel, the heat transmission rates and heat liberation rates expressed in B.Th.U. are in accordance with the suggestions contained in the paper. In connection with test periods, I am of the opinion that even 24 hours is far too short. The suggestion put forward by Mr. Jockel for the elimination of air-heater ducts is interesting, but I do not consider that the cost of the regenerative units would show any saving over the usual form of ducting.

In reply to Mr. Damant, the figure of 3d. per ton for milling costs does not include the cost of electrical energy and, in my opinion, is well within the bounds of possibility. As they vary considerably, it is difficult to give prices for bull rings and rollers for ring and roller-type mills, but Mr. Damant should have no difficulty in obtaining representative prices from the manufacturers of this type of mill and also from the principal English steel makers, a number of whom now specialize in the production of these items of milling equipment. In connection with the test results given in Tables 2 and 3 and the general improvement in plant performance during the first year of operation, various modifications were carried out. The principal factors affecting this improvement were: increase in fineness and better drying of the milled product, alterations to the front-wall air ports, careful calibration and setting of the front-wall multiple dampers, and greater efficiency of the operating staff. The loss due to carbon in the ash is measured in the usual way, namely, by carefully removing all the refuse after the combustion of the initial weight of coal, weighing this refuse and finally quartering, sampling, and testing for combustible content, this latter item being calculated as carbon. The following are the principal dimensions of the furnace of the type of boiler unit shown in Fig. 3:

Mean height, water screen to boiler tubes ..	27 ft. 3 in.
Length	31 ,, 0 ,,
Width at centre	17 ,, 10 ,,
Front wall to centre line of burners ..	4 ,, 0 ,,

The capital cost of plant for dust-extraction purposes varies between 3s. and 6s. per kilowatt of boiler-plant capacity so equipped. This figure is based on a water rate of 10 lb. per kilowatt. Disposal of the dust arrested is not a very difficult matter, particularly if the main plant is equipped with a hydraulic system of ash sluicing. Further, it is likely that in the near future a market will be available for this fine dust; in which case the cost of installing automatic bag-filling gear may be justified.

SOME ACOUSTIC AND TELEPHONE MEASUREMENTS.

By H. R. HARBOTTLE, B.Sc.(Eng.), Associate Member.

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SUMMARY.

In the present paper a brief description of some of the work carried out in the Research Section of the British Post Office is given. Part 1 is devoted to electro-acoustic and acousto-electric measurements of instruments. In Part 2 various voice-ear measurements on microphones and receivers are described. Part 3 deals with some mechanical tests by means of which rapid acceptance tests and estimates of the commercial life of instruments can be made. The question of the measurement of the efficiency of apparatus and circuits in actual use is discussed in Part 4.

UNITS AND ABBREVIATIONS USED IN THE PAPER.

Mile of Standard Cable (*British*) (*m.s.c.*).—One mile of a cable having the following constants per loop mile:—

Resistance $(R) = 88$ ohms.
Capacitance $(K) = 5{\cdot}4 \times 10^{-8}$ farad.
Inductance $(L) = 1 \times 10^{-3}$ henry.
Leakance $(G) = 1 \times 10^{-6}$ mho.

The *Standard Mile* (*s.m.*).—The attenuation of 1 mile of standard cable at 800 cycles per sec. This unit was also known as the 800-cycle mile.

At 800 cycles 1 mile of standard cable has an attenuation of 0·1065 néper.

The *Néper* is the natural attenuation unit and is defined in the following manner:—If I_1, E_1, and I_2, E_2, are the currents and voltages at two points along a uniform infinite line, then the attenuation between these two points is given by

$$\log_e \frac{I_1}{I_2} = \log_e \frac{E_1}{E_2} \text{ népers}$$

It will be seen at once that these currents and voltages are measured across equal impedances.

The *Bel*.—The attenuation between two powers is said to be 1 bel when the logarithm to the base 10 of the ratio of the powers is unity, i.e. the attenuation between two powers P_1 and P_2 is 1 bel if

$$\log_{10}(P_1/P_2) = 1 \quad \text{or} \quad P_1/P_2 = 10$$

and 2 bels if

$$\log_{10}(P_1/P_2) = 2 \quad \text{or} \quad P_1/P_2 = 100 = 10^2$$

etc.

The *Decibel* is one-tenth of the above unit.

INTRODUCTION.

The progress in acoustical engineering in recent years, and the possibility of expressing the results of measurements in telephony by reference to absolute units, can probably be attributed to the invention and development of the thermionic valve. This has permitted the investigation of methods for measuring acoustic pressures and velocities and made possible the rapid developments in radio-telephony. As a direct result of the latter, world-wide telephonic communication—one of the ultimate aims of telephone engineers for many years—has been made possible. For the successful operation of such an achievement the necessity for comparative measurements of the performance of instruments, apparatus, lines, etc., soon became apparent. This led to the formation of an international committee—the C.C.I.*—the objects of which were, amongst others, the formulation of the correct methods of measurement of the above and the most convenient manner of expressing the results in terms of absolute units.

As regards the instruments, some standards were needed which were constant in their performance and had a uniform frequency/response characteristic over the range in which it was intended they should be used. At the present moment this can only be achieved by the use of insensitive instruments in which the mechanical resonances have been removed to frequencies outside the desired limits by means of increased or, alternatively, reduced mechanical or acoustical stiffness. The output from these instruments can now be raised to the required level by a suitably-applied thermionic-valve amplifier.

Instruments fulfilling the above conditions are usually of a delicate mechanical construction and unsuitable for commercial use. However, when under the direct supervision of experts, a wide field has been found for them in broadcasting, talking pictures, gramophone reproduction, etc., apart from the original purpose for which they were designed. Commercial instruments in which a high electro-acoustic efficiency is required must still rely on suitably-applied mechanical and acoustical resonances. By dint of careful design the reproduction of speech from some of these instruments is surprisingly good, although the frequency/response characteristics are not sufficiently uniform, and their performance not constant enough, to permit their use as standards for measurement purposes.

PART I. ACOUSTO-ELECTRIC AND ELECTRO-ACOUSTIC MEASUREMENTS.

The instrument used at the present time as a working standard in most acousto-electric and electro-acoustic measurements is a condenser microphone of the Wente type.† This consists essentially of a stretched, thin, duralumin diaphragm, 4·286 cm effective diameter, which is gold-plated or varnished on its external face

* Comité Consultatif International des Communications Téléphoniques à Grande Distance.
† See Bibliography, (1).

to prevent oxidization, forming one plate of an air condenser, the other plate being a circular insulated brass electrode. This is grooved on the face presented to the diaphragm and is separated from the latter by a small gap. The air space between the diaphragm and the back electrode is practically sealed and serves as an added stiffness to the diaphragm. Due to this and to the stretching, the frequency of natural resonance of the diaphragm is effectively suppressed. The instrument is consequently rather insensitive but is very constant in its performance.

The microphone is polarized by 200 volts (d.c.) which is fed via a resistance of 10 megohms or more. Acoustic pressures on the diaphragm cause corresponding changes in capacitance of the microphone. These in turn vary the p.d. across it, the charge remaining constant. As the variation in capacitance of the microphone produced by impressed sound is very minute, the microphone can be regarded as an alternator having an e.m.f. proportional to the acoustic pressure on the diaphragm, and an internal impedance equal to its normal capacitance when polarized. The value of this capacitance is about 300 $\mu\mu$F. The absolute calibration of the condenser microphone is performed by three distinct methods*:—

(1) *The Thermophone Method.*—This method is used in America and is recommended by the C.C.I.

The diaphragm of the microphone forms one end of a small cylindrical air-tight chamber. The other end of the chamber is closed by means of a mounting plate which carries two thin strips of gold-leaf side by side, each about 2·54 cm by 1 cm. The volume of the chamber is approximately 9 cm^3. The chamber is filled with hydrogen at atmospheric pressure. A known direct current is passed through the strips, and a known alternating current of the required frequency is superimposed on this. The alternating current causes alternate heating and cooling of the strip at the applied frequency, which in turn causes an alternating pressure on the diaphragm of the microphone. It is essential for the calculation of this pressure that the pressure produced by the alternating current in the foils be transmitted instantaneously to all parts of the chamber. Hence the necessity for a small chamber and for this to be filled with hydrogen, since the wavelength of a particular frequency in hydrogen is four times that in air. Wente has obtained an expression for the pressure developed at the diaphragm. Reference to the original publication† shows that the calculation of pressure is rather involved, and this, together with the fact that the diaphragm of the microphone is in a more or less hypothetical condition due to the added stiffness caused by the 9 cm^3 of hydrogen, are disadvantages of the method. However, the conditions are all capable of being specified and can be repeated at long intervals.

(2) *The Rayleigh-Disc Method.*—If the nature of a sound field is known, then a definite relationship exists between the acoustic pressure, p, and the velocity, v, and it is therefore only necessary to measure one in order to determine both.

If we have a point source of sound‡ in a perfectly non-reflecting chamber the resultant sound waves produced will be truly spherical. In this case Mallett and Dutton* have shown that the instantaneous particle velocity is given by:—

$$v = \frac{A}{4\pi}\left\{-\frac{1}{r}\cdot\frac{\omega}{c}\sin\omega\left(t-\frac{r}{c}\right)+\frac{1}{r^2}\cos\omega\left(t-\frac{r}{c}\right)\right\}$$

and the instantaneous pressure by:—

$$p = -\frac{A\rho}{4\pi r}\omega\sin\omega\left(t-\frac{r}{c}\right)$$

where r = radial distance of the point from the source,
$\omega = 2\pi \times$ frequency,
ρ = density of medium,
c = velocity of sound in medium,
and A = constant.

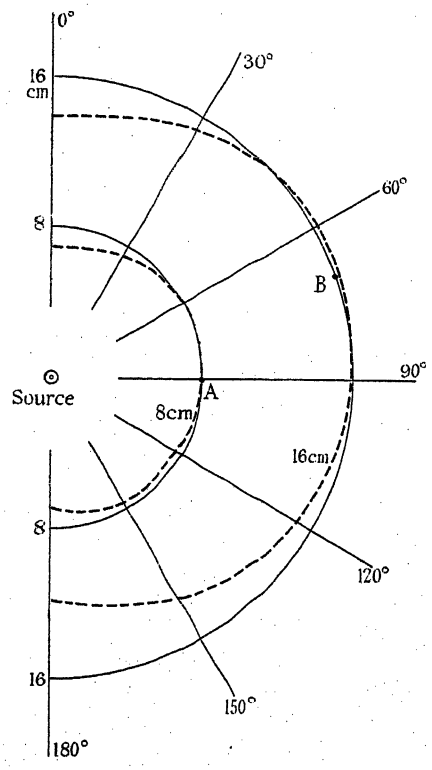


FIG. 1.—Sound-field chart of acoustic cabinet. Frequency = 480 cycles per sec.

The R.M.S. values of the above are:—

$$V = \frac{A}{4\pi\sqrt{2}}\sqrt{\left[\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right]}$$

and

$$P = \frac{A\rho\omega}{4\pi r\sqrt{2}}$$

This latter gives a convenient method for determining when the sound wave is spherical, for in this case $P \propto 1/r$, i.e. Pr = constant.

Now, at very large distances, r being great, it will be apparent that the wave will be approximately planar. When this is the case

$$V = \frac{A\omega}{4\pi\sqrt{(2)}rc}$$

* See Bibliography, (2). † *Ibid.*, (3). ‡ *Ibid.*, (4).

* See Bibliography, (5).

and $$P = \frac{A}{4\pi\sqrt{2}} \cdot \frac{\rho\omega}{r}$$

Hence for a plane wave

$$\frac{P}{V} = \rho c$$

For air at normal room temperature and pressure

$\rho = 0{\cdot}0012$ gramme/cm^3 and $c = 34\,000$ cm/sec.

Therefore $$\frac{P}{V} = 40{\cdot}8$$

Lord Rayleigh* pointed out in 1881 that if a light disc were suspended in a sound field it would tend to set itself with its plane at right angles to the field. When the disc is an ellipsoid, König† has shown that the steady torque on the disc is

$$\frac{1}{6}\rho d^3 V^2 \sin 2\theta$$

The maximum value of this torque is when $\sin 2\theta = 1$, i.e. $\theta = 45°$. The sensitivity is proportional to the cube of the diameter of the disc, but if this diameter is greater than 0·2 wavelength sensible errors may be introduced owing to a variety of reasons. Again, with greater sensitivity, the precautions to be taken against draughts are much greater and the disc is also not so dead-beat. The discs in the Research Section of the British Post Office are made circular of mica 0·002 cm thick and 0·8 cm diameter. Although these are not ellipsoids, the errors introduced by using König's formula are sufficiently small to be neglected. This question has been dealt with fully by Barnes and West.‡

The Box Method.—This method was first suggested by Mallett and Dutton.§ The box used by the Research Section of the British Post Office is 4 ft. cube and is lined on all six internal walls by gamgee tissue to a depth of 12 in. The source of sound used for frequencies of 300 to 1 000 cycles per sec. is a tube closed at one end by an ordinary telephone receiver having the ear-cap cut away. The length of the tube is adjustable. The source of alternating current for the receiver is a heterodyne oscillator the frequency of which is adjusted to coincide with that of one of the resonances of the tube. The diameter of the mouth of the tube is 7 cm, and Mallett and Dutton have shown that, for the range of frequencies covered, this can be treated as a point source at distances greater than 6 cm.

For frequencies of 1 000 to 3 000 cycles per sec. the tube is terminated by a conical end having an aperture of 2 cm in order to reduce the size of the source, and for frequencies above 3 000 cycles per sec. by a receiver having a diaphragm of small diameter and, therefore, a high fundamental resonant frequency. In front of the diaphragm a small adjustable Helmholtz resonator is fitted to purify and intensify the output sound.

The Rayleigh disc is suspended by means of a fine glass fibre at a horizontal axial distance of approximately 8 cm from the mouth of the tube, and the condenser microphone at approximately 20 cm in the same plane in a convenient position. In these positions it will be seen by reference to Figs. 1 and 2 that reflection from the walls of the box is negligible. These curves were obtained in the manner suggested by Mallett and Dutton and are explained below.

A Bell receiver was fitted with a conical brass tube about 18 in. long. The internal diameter of the tube was the same as that of the hole in the ebonite earcap,

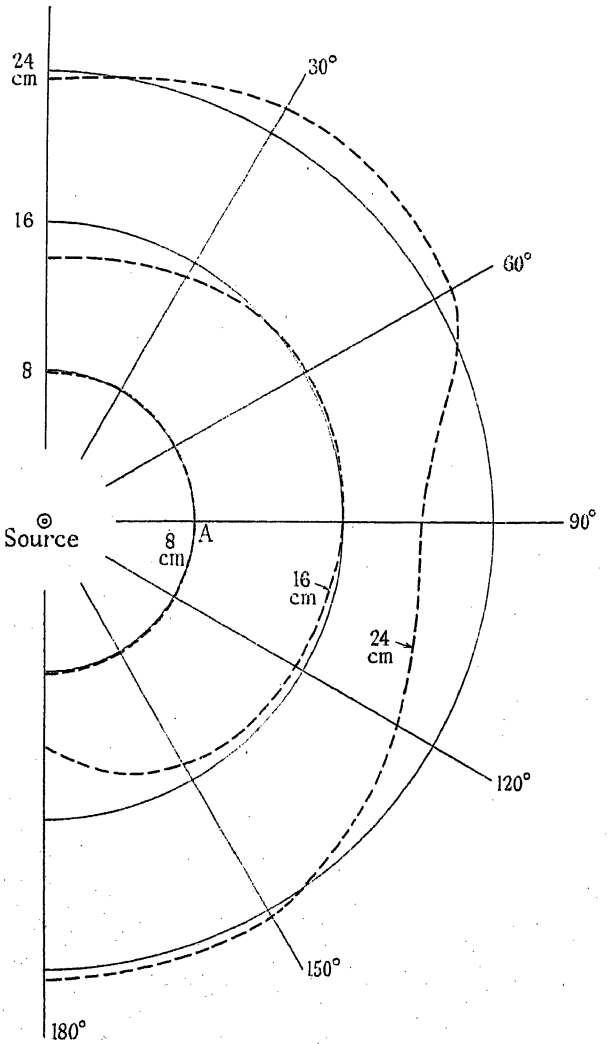


FIG. 2.—Sound-field chart of acoustic cabinet. Frequency = 600 cycles per sec.

viz. about 1 cm, and the outside diameter tapered from 6 cm at the receiver to 1·5 cm at the mouth. The receiver was moved in the box, so that the mouth of the conical tube described a semicircle having for its centre the centre of the mouth of the source of sound. The frequency of the source was maintained constant and the output from the receiver was measured on a valve voltmeter for the various positions. This was a measure of the acoustic pressure at these points. A simple computation gave the distance from the source at which the pressure occurred which would have existed at the circumference of the semicircle with no reflection.

Suppose P is the pressure which, neglecting reflection,

* See Bibliography, (6). † *Ibid.*, (7). ‡ *Ibid.*, (8). § *Ibid.*, (5).

would have existed at the circumference of a semicircle of radius r cm, and that P' was the actual pressure measured at this radius, then it was assumed that

$$P' \times r = P \times r'$$

where r' is the distance at which the pressure P actually occurred with reflection present. The corresponding values of r' are plotted on the dotted-line curves.

The deflection of the disc is measured by means of a lamp and scale. From the deflection of the disc the velocity of the sound wave can be calculated, and hence, since the sound field is known, the sound pressure which existed at the position of the condenser microphone before the microphone was put there.

The actual pressure on the diaphragm will differ from the above by a ratio which will vary between 1 and 2, depending on the frequency and the diameter of the microphone and also to a very large extent on the form of the cavity in front of the diaphragm. The output

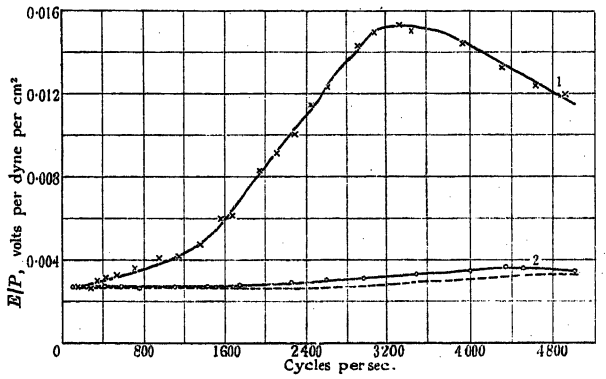


FIG. 3.—Frequency characteristics of standard reference type of condenser transmitter.

Curve 1 in terms of free air pressures.
Curve 2 in terms of pressures on diaphragm.
Broken curve shows maker's calibration by thermophone.
Polarizing voltage = 200 volts.

from the condenser microphone due to this pressure on the diaphragm is amplified by means of a suitable resistance-capacitance-coupled amplifier and conveniently measured on a Moullin voltmeter. Since the sound pressure on the diaphragm of the microphone will be sinusoidal, and as the amplitude characteristic of the microphone is linear, the voltmeter reading will be a measure of the R.M.S. value of the e.m.f. from the microphone. The calibration of the amplifier is most easily done by feeding a sinusoidal alternating current of about 5 mA into a non-reactive resistance connected in series with the microphone at the earth end.

The "Tube" Method.—This method is due to W. West.* The Rayleigh disc is suspended at the centre of a long tube, the length of which can be adjusted. The source of sound, which is a moving-coil receiver, is fitted into one end of the tube, the microphone closing the other end. At resonance, there will be a loop of velocity at the centre of the tube and a loop of pressure at the ends. The sound waves will be planar and hence the relationship $P/V = \rho c$ holds. One setting of the tube can be used for observations at a series of frequencies, if these frequencies are odd harmonics of the frequency of fundamental resonance of the tube. The resonance of the tube is very sharp and hence the test is a comparatively simple one.

Fig. 3 gives the frequency characteristics of a condenser microphone obtained by the three methods described above. The difference between curve 2 and the dotted curve is accounted for as follows:—With the thermophone calibration, there is a sealed cavity in front of the diaphragm which increases its stiffness, whereas with the tube method, since the tube is in resonance, the air in the tube adds a small resistance to the diaphragm.

It would be expected that the numeric obtained by the box method would be the same as that with the tube method for frequencies up to 500 cycles per sec., and increase to twice that of the latter as the frequency is increased. However, the surprising increase in the numeric shown in curve 1 must be due to some resonance —that of the cavity in front of the diaphragm. This question has been ably investigated by West* and Ballantine.† The particular calibration to be taken will depend on how the condenser microphone is to be used.

(3) *The Compensator Method.*—The pressure developed in the chamber used with the thermophone method of calibration is measured in Germany by means of a compensator. This is due to Gerlach‡ and is briefly as follows:—

A strip of foil is set in motion by the sound pressure on it and is brought to rest either electromagnetically or electrostatically by means of a suitably applied, known, alternating current or voltage of the same frequency as that of the impressed sound and capable of variation in amplitude and phase. An arrangement is incorporated by which the balance of the strip can be ascertained. The chief feature of this method is that the strip is at rest at balance.

Comparison with the tube method has been made in the Research Section of the British Post Office and close agreement obtained.

THE FREQUENCY CHARACTERISTICS OF COMMERCIAL MICROPHONES.

The calibration of the condenser microphone performed in any of the methods previously described is necessarily a point-to-point measurement. Such a method is obviously unsuitable for commercial microphones, especially those of the carbon-granule type owing to their tendency to pack. The method used for testing such microphones in the Research Section of the British Post Office is as follows:—The acoustic pressure on the microphone diaphragm is supplied by means of a special loud-speaker consisting of a moving-coil instrument connected to a wooden exponential horn 15 ft. long. The flare of this horn forms part of one wall of an acoustic room and is $3\frac{1}{2}$ ft. in diameter, and hence it can be used down to 100 cycles per sec.

A brief description of the acoustic room may be given here. The room is 12 ft. by 9 ft. by 9 ft. high and is lined to a depth of 1 ft. 6 in. with gamgee tissue backed with celotex. In addition fins 6 in. wide at right angles to the walls and ceiling are arranged at intervals of 6 in.

* See Bibliography, (9).

* See Bibliography, (10). † *Ibid.*, (11). ‡ *Ibid.*, (12).

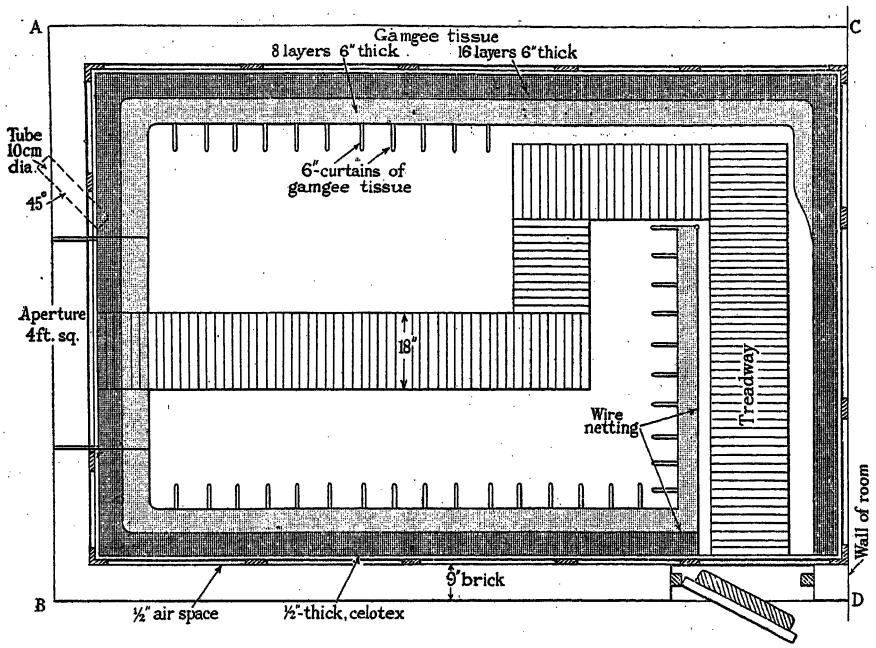


FIG. 4.—Plan of acoustic chamber.

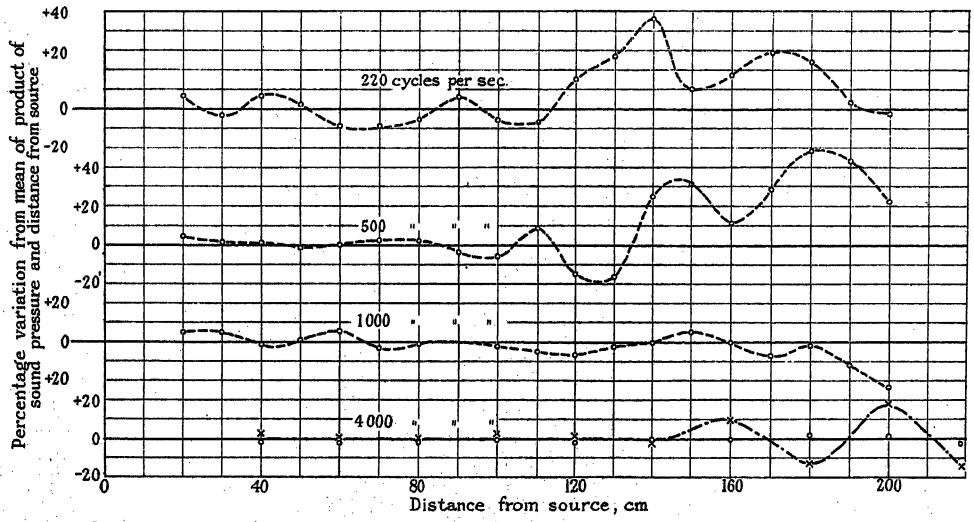


FIG. 5.—Sound-field explorations in acoustic cabinet.

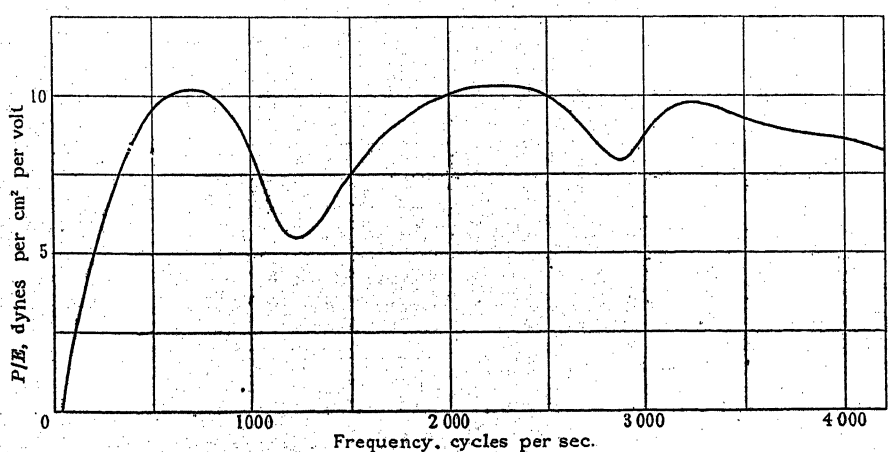


FIG. 6.—Output/frequency characteristic of moving-coil unit on exponential horn.

(see Fig. 4); "$p \times r$" curves show that reflection has been substantially eliminated. Some of these curves are reproduced in Fig. 5.

The output from the exponential horn is measured by means of a condenser microphone located at the centre of the plane of the flare. Fig. 6 gives the output-frequency characteristic of the moving-coil unit used in this manner.

The microphone to be tested is put in the position of the calibrating microphone, and its output on any required circuit is applied to a straight-line amplifier-rectifier which operates a quick-moving galvanometer. The amplifier is resistance-capacitance coupled and the rectifier used is a low-impedance diode connected in series with a resistance of 100 000 ohms, so that changes in impedance of the valve for different inputs are masked, giving a practically linear response.

The loud-speaker is operated from a heterodyne oscillator, the frequency of which is varied by means of a condenser inside a cylindrical drum carrying the paper on which the frequency characteristic is drawn. The spot of light from the galvanometer of the amplifier-rectifier moves over this paper, and its path is traced by means of various coloured pencils. Typical frequency characteristics obtained on two types of carbon microphones are given in Fig. 7. From these it can be estimated that the microphone of the hand micro-telephone is not only more efficient but will reproduce speech more faithfully than the C.B. No. 1. This will be referred to later.

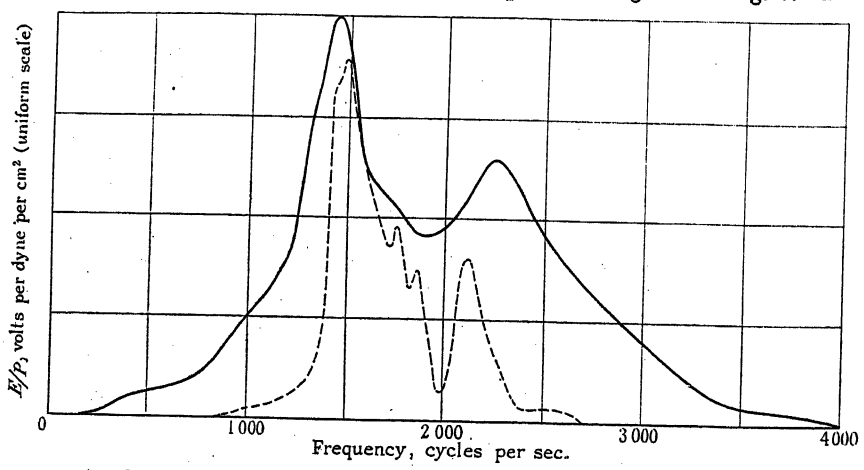


FIG. 7.—Frequency characteristics of carbon microphones.
——— Hand micro-telephone.
— — — C.B. No. 1.

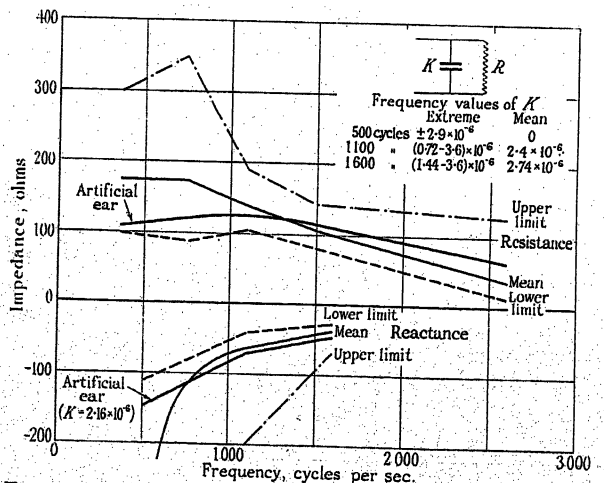


FIG. 8.—Acoustic impedances due to ears on standard earcap.

FREQUENCY CHARACTERISTICS OF RECEIVERS.

The frequency characteristic of a receiver is governed to a large extent by the acoustic impedance added to the diaphragm. In use, this impedance is that due to the ear, and West* has shown that this can be treated as an elastic reactance in parallel with a resistance. The values of these components over a frequency range obtained on a large number of human ears, when pressed to the standard earcap, are included in Fig. 8. How-

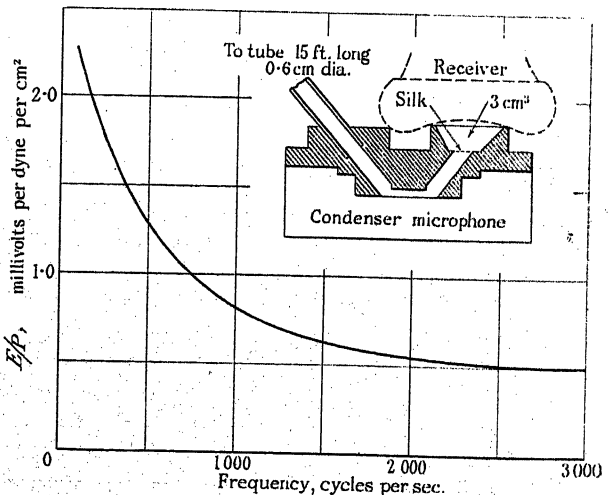


FIG. 9.—Frequency characteristic of condenser microphone in artificial ear.

* See Bibliography, (13).

ever, it is impossible to measure the output of a receiver when held to the average human ear, and two methods are available which surmount the difficulty to a large extent.

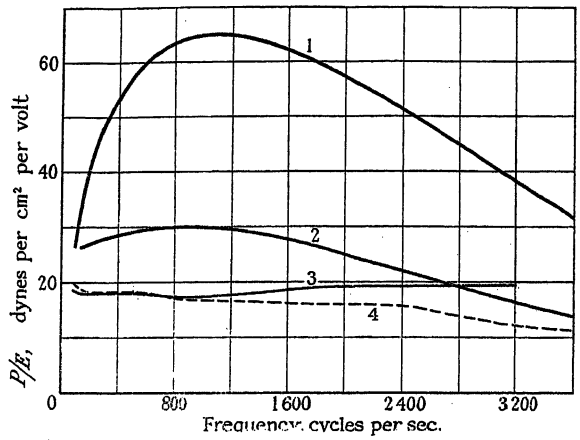


FIG. 10.—Frequency characteristics of standard reference type of moving-coil receiver.

Curve 1.—On artificial ear with 3·5 cm³ air space.
Curve 2.—On artificial ear with 9 cm³ air space.
Curve 3.—On standard type S.F.E.R.T. coupler with 27 cm³ air space.
Curve 4.—Maker's calibration on standard S.F.E.R.T. coupler.

(1) *The C.C.I. Coupler.*—This method is used in America, and by the C.C.I. on the S.F.E.R.T.* for calibrating high-quality moving-coil receivers. The receiver, in this case, is acoustically coupled to a condenser microphone by means of a sealed chamber which has a volume of 27 cm³ and is filled with hydrogen at atmospheric pressure. The output from the receiver is measured by the condenser microphone. This method applies an acoustic elastance only to the receiver diaphragm, and this elastance is much smaller than that of the average human ear.

(2) *The Artificial Ear of the British Post Office.*—This is due to West.* In this case, the receiver is coupled to a condenser microphone via a chamber having a volume of 3 cm³ which communicates with a brass tube 15 ft. long and 0·35 cm² cross-section. Strands of darning wool varying in length from 6 ft. downwards are drawn into the tube and produce an increasing absorption from the microphone end to the free end of the tube. The arrangement thus presents an acoustic elastance and resistance in parallel with the receiver diaphragm. The particular values of the components chosen were the mean of those obtained on human ears when pressed to a standard earcap, at a frequency of 1 100 cycles per sec., the average frequency of the fundamental resonance of the diaphragm of Bell receivers when held to the human ear.

The effect of the increased stiffness imposed on the diaphragm of the condenser microphone used in the artificial ear is clearly demonstrated by Fig. 9. The microphone is calibrated in terms of pressures existing at the mouth of the flare of the cavity of the artificial ear, and the associated amplifier is distorted in such a manner as to secure a substantially uniform frequency/response characteristic of microphone and amplifier combined.

The difference in the effect of the two couplers described above, on the performance of a moving-coil high-quality receiver such as is used on the S.F.E.R.T., will be appreciated by reference to Fig. 10. The difference between curves 3 and 4 is probably explained by the fact that, when taking the former, air was used in the coupler, whereas in the latter hydrogen was substituted.

In order further to emphasize the importance of the

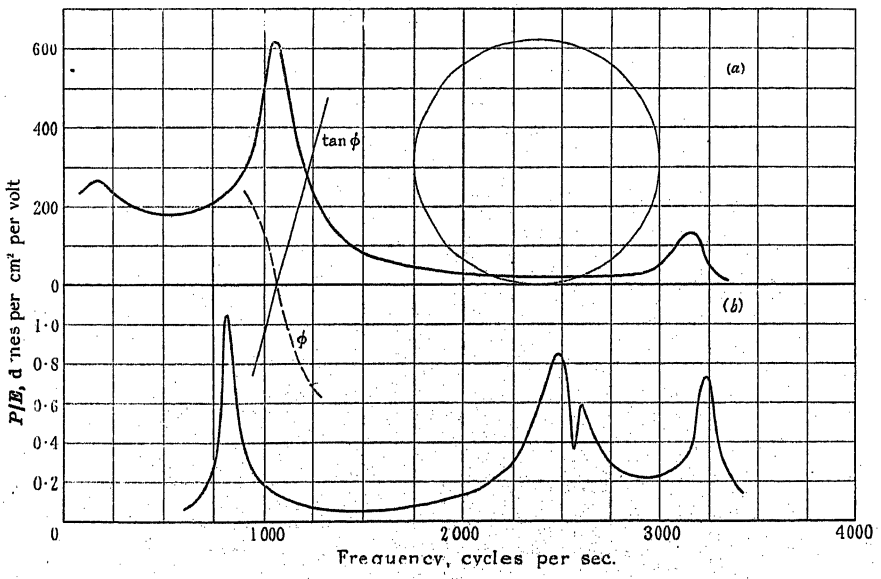


FIG. 11.—Frequency characteristics of a Bell receiver.

(*a*) Sound pressures when held to an ear.
(*b*) Sound pressures at 10 cm distance in open air.

* Système Fondamental Européen de Référence pour la Transmission Téléphonique.

* See Bibliography, (14).

correct added acoustic impedance, when obtaining the frequency characteristic of receivers, Fig. 11 has been added.* Referring to this figure, it will be evident that the effect of the added acoustic impedance of the artificial ear is twofold. Firstly, the output pressure is increased enormously. This is to be expected, since in open air the receiver is radiating sound and this very inefficiently, but when held to the artificial ear the movement of the diaphragm is simply developing an acoustic pressure in a small chamber. Secondly, there is a distinct improvement in frequency characteristic with a consequent increase in the fundamental resonant frequency of the diaphragm. Impedance curves for the same receiver under the two conditions are given in Fig. 12. The frequency of the fundamental resonances of the diaphragm and the decay factors obtained from Figs. 11 and 12 are in very close agreement. In Appendix I the calculation of the mechanical constants of the diaphragm (neglecting the added elastance caused by the cavity behind the diaphragm) from the change in resonant frequency and decay factor produced by the change in acoustic impedance applied to the diaphragm is demonstrated. For the diaphragm of the receiver tested, the constants were found to be approximately:—

Resistance = 263 dynes/cm/sec.
Stiffness = $15{\cdot}5 \times 10^6$ dynes/cm.
Equivalent mass = 0·54 gramme.

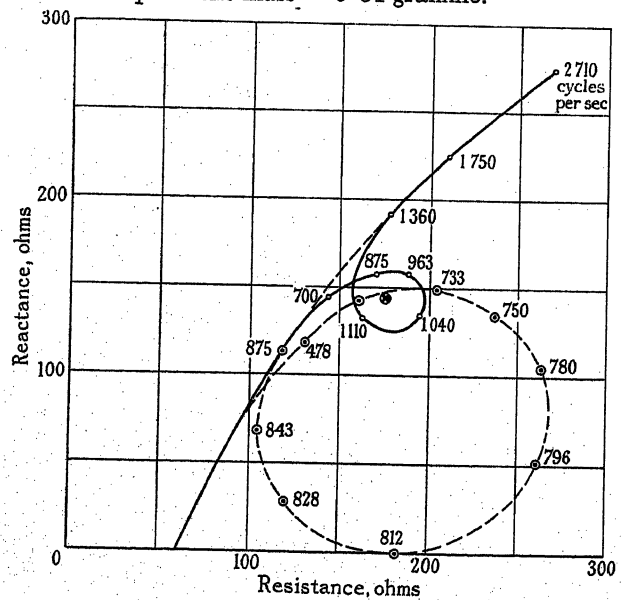


FIG. 12.—Impedance of Bell receiver.
——— Receiver held to artificial ear.
— — — Receiver in free air.
* Impedance with speech.

These are in good agreement with the figures published by Kennelly.†

FREQUENCY CHARACTERISTICS OF LOUD-SPEAKERS.

When a loud-speaker is to be tested it is placed in the acoustic room described, on page 608, its output being measured by means of a condenser microphone previously calibrated. The output from the condenser microphone and its amplifier is measured on the recorder described above. The output from the heterodyne oscillator passes to the grid of the valve to the anode of which the loud-speaker is suitably connected.

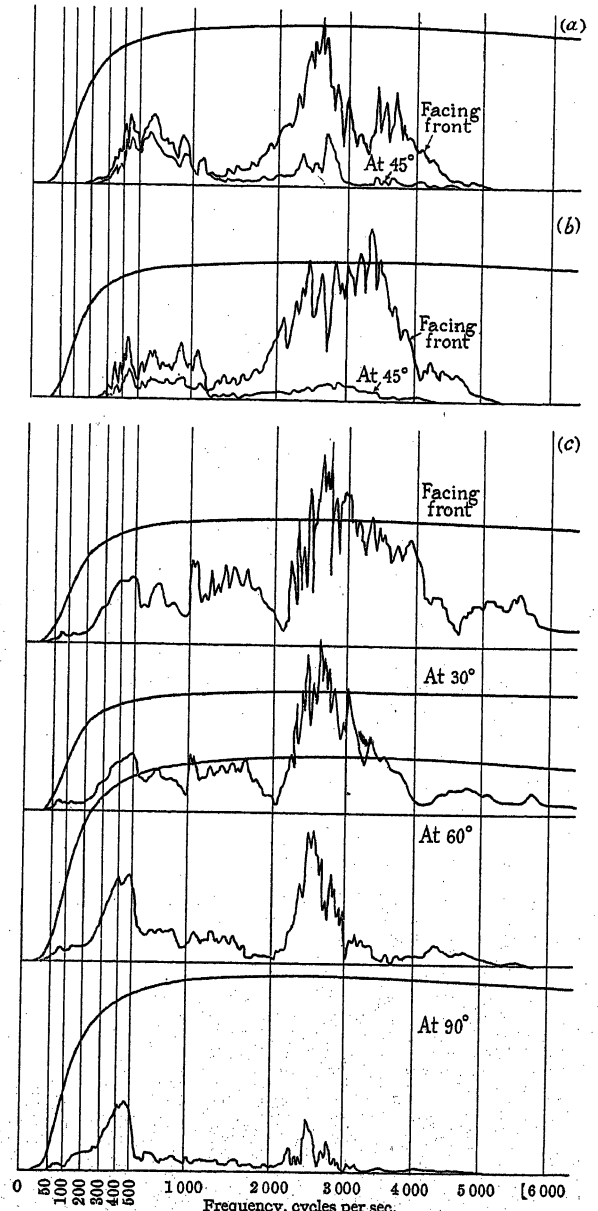


FIG. 13.—Loud-speaker frequency characteristics.
(a) Reed-driven cone in cabinet; back closed; cone angle about 120°.
(b) Reed-driven cone in cabinet; back closed; annular guard-rings in front; cone angle about 120°.
(c) Moving coil in box baffle about 18 in. cube, with metal flare extending cone to front of box.

When once the testing circuit has been set up and made free from induction by suitable disposition of earths and necessary balancing, it is a simple matter to perform these tests. Sample curves taken in this manner on some commercial types of loud-speakers at different angles to the flare are reproduced in Fig. 13.*

* See Bibliography, (21). † *Ibid.*, (15).

* Also see Bibliography, (16), (17), (18), (19), and (20).

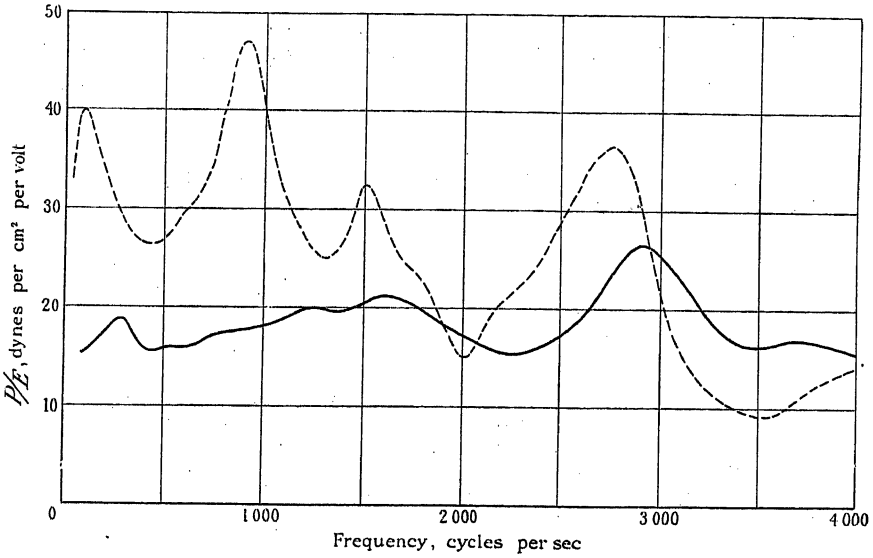


FIG. 14.—Performance of moving-coil loud-speaker fitted with earcap held to artificial ear.
——— Impedance. — — — Sound output.

By a slight modification of the circuit it is possible to obtain the performance of the loud-speaker alone, its impedance, the electrical power given to it, and its electro-acoustic efficiency, using the 3-voltmeter method. The output from a moving-coil receiver when held to the artificial ear, together with its impedance obtained as above, are given in Fig. 14.

PART 2. VOICE-EAR MEASUREMENTS.

The frequency/response characteristics of commercial telephone instruments, which, in general, have not a

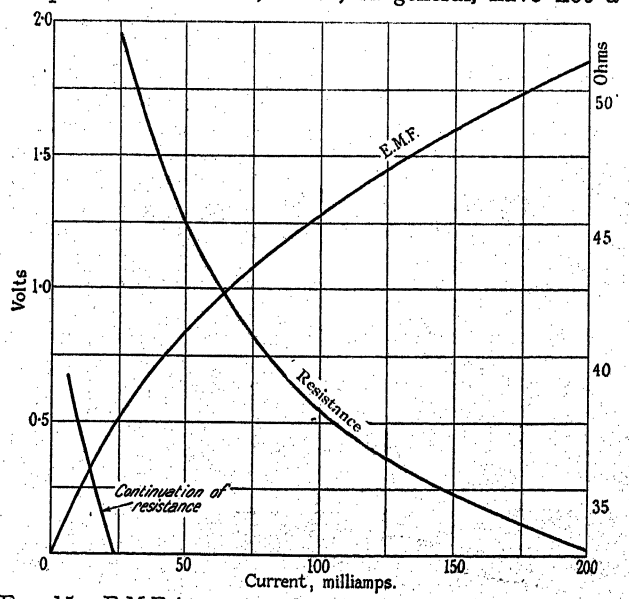
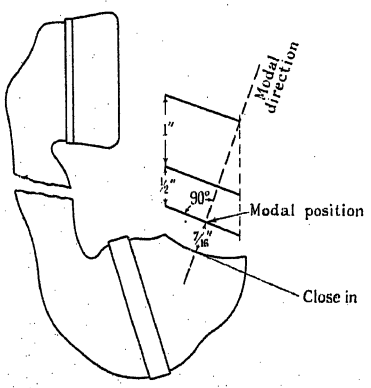


FIG. 15.—E.M.F./current and resistance/current curves for microphones type No. 1 W.E. Mark 4001, in vertical position.
E.M.F. curve—based on 21 W.E.-type microphones.
Resistance curve—based on 8 W.E.-type microphones.

reasonably uniform performance over the frequency range required for the successful transmission of speech, give a considerable amount of qualitative information as to the performance of these instruments in practice



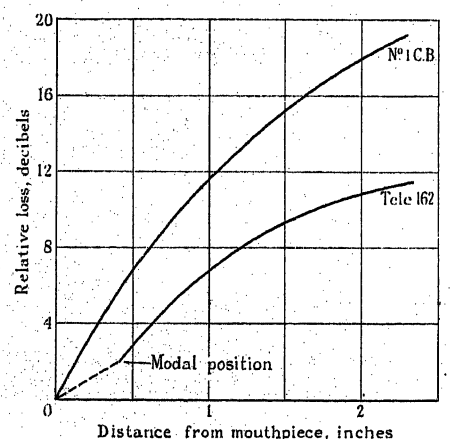


FIG. 16.—Effect of speaking at a distance from the mouthpieces of No. 1 C.B. and Tele. 162 microphones.

and are extremely useful in design. They have often led to the explanation of differences obtained by other

methods of measurement. However, the only measurements which, at present, give definite quantitative results on these instruments are obtained from voice-ear tests. Here, again, such measurements can only be considered reliable if a sufficient number of tests are made, and these of a very detailed nature under conditions similar to those met with in practice. Voice-ear measurements will always be the final arbiter in telephone problems. A description will now be given of some of these measurements as applied to carbon microphones and commercial receivers.

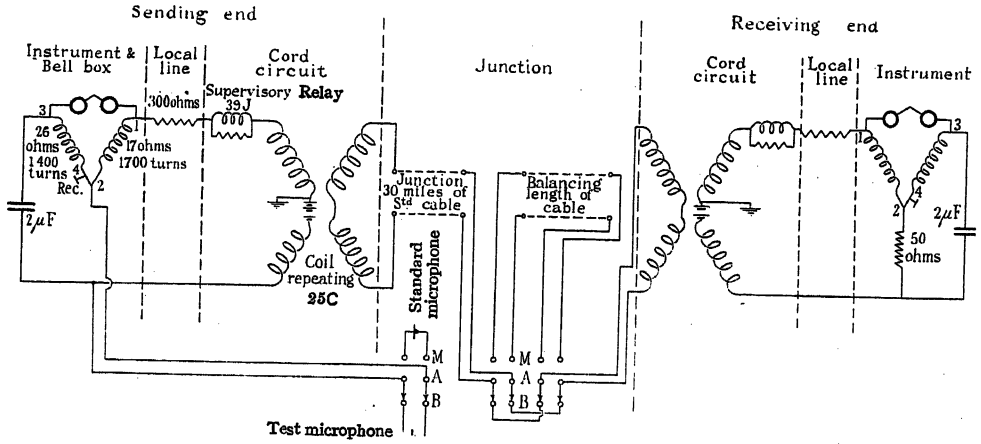


FIG. 17.—Standard common-battery circuit.

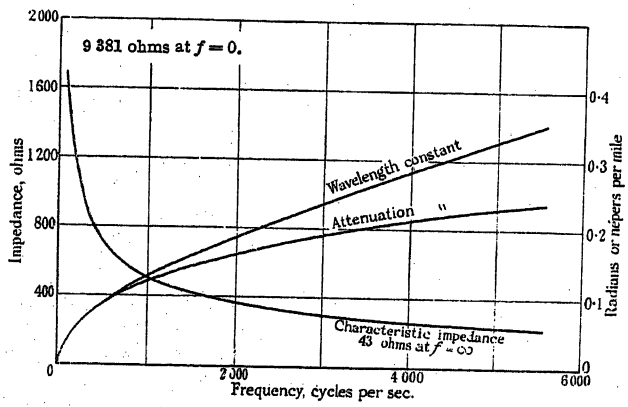


FIG. 18.

Constants of standard cable per loop mile:—
$R = 88$ ohms.
$K = 0{\cdot}054 \times 10^{-6}$ farad.
$L = 1 \times 10^{-3}$ henry.
$G = 1 \times 10^{-6}$ mho.

Microphones.

The performance of a carbon microphone depends to a large extent on the following factors:—

(1) The circuit in which it is connected. This will determine the feeding current to the microphone, and reference to Fig. 15 will illustrate clearly the extent to which the e.m.f. of a carbon microphone is dependent on the feeding current. Also, the impedance into which the microphone is working is a function of the circuit in which it is connected.

(2) The initial condition of the carbon granules themselves.

(3) The sound pressure on the microphone diaphragm. This will be affected by the type of mouthpiece fitted to the microphone, by the position of the speaker's mouth relative to the mouthpiece, and by the volume of sound emitted from the speaker's mouth. The reduction in output from two types of carbon microphone caused by the speaker increasing the distance of his mouth from the mouthpiece, is given in Fig. 16. A decrease in a speaker's volume will cause a similar reduction in output.

(4) The angle at which the microphone is mounted. This will be more important with solid-back types of microphones than with the new hand micro-telephones.

In order that condition 1 may be satisfied a standard circuit is required. The circuit used by the British Post Office until a comparatively short time ago is known as the "standard common-battery circuit."

The Standard Common-Battery Circuit.

A schematic diagram of this circuit is given in Fig. 17. The sending and receiving terminations of the junction

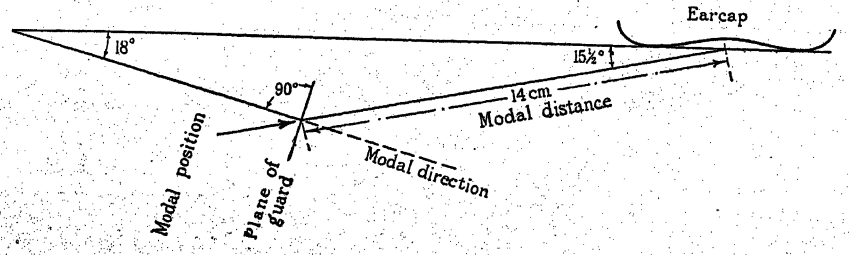


FIG. 19.

on this circuit each consist of a standard common-battery cord circuit (repeating coil and supervisory relay), a local line, and a standard common-battery subscriber's instrument and bell box. The local line used is a non-reactive resistance of 300 ohms, and it is interesting to note that the average subscriber's local line is taken as $\frac{3}{4}$ mile of $6\frac{1}{2}$-lb. underground cable, which has a loop resistance of 204 ohms and a capacitance of $0{\cdot}046\ \mu$F, connected to $\frac{1}{8}$ mile of 40-lb. bronze aerial line, having a loop resistance of 11 ohms and negligible capacitance, at the subscribers' end. The instruments and apparatus are made up of parts selected as standard for the type from a.c. impedance, d.c. resistance, and speech tests. The operating battery is of 22 volts. Under these conditions the feeding current to the microphone is of the order of 50 mA. The junction used on the standard common-battery circuit is 30 miles of artificial standard cable. The primary and secondary

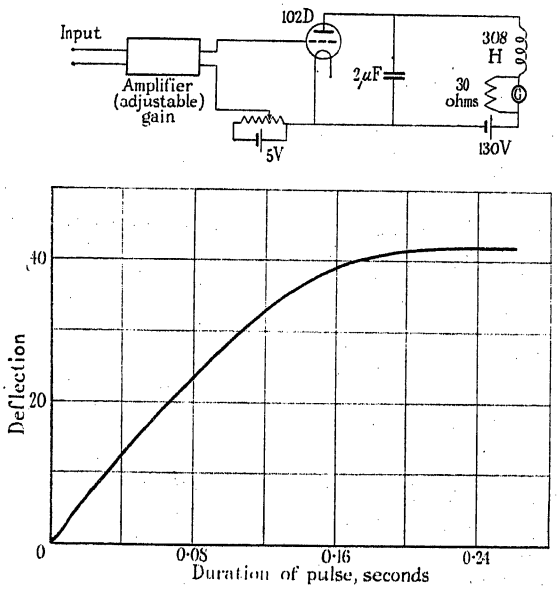


FIG. 20.—Volume indicator.

constants of this cable are given in Fig. 18. Thus, the impedance into which the microphone is operating, measured at 800 cycles per sec., is $200/\underline{0°}$ (approx.).

The above circuit having a zero-ohm local line was also used as a standard of reference.

The contemporary standard circuit used in America was similar to the above, with the following exceptions:—

(*a*) The American circuit had a 24-volt battery.

(*b*) The supervisory relay was omitted.

(*c*) The local line consisted of 3 miles of American standard cable.

(*d*) The artificial standard cable used had no leakance and inductance, the resistance and capacitance per loop mile being the same as those of British standard cable.

The propagation constant of the American standard cable at $\omega = 2\pi f = 5\ 000$ is given by

$$p = \sqrt{(j\omega KR)} = \sqrt{(\omega KR)}\ \underline{/45°} = 0{\cdot}1542\ \underline{/45°}$$
$$= 0{\cdot}1091 + j0{\cdot}1091*$$

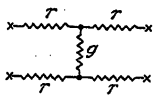
* See Bibliography, (22).

as compared with $p = 0{\cdot}1062 + j0{\cdot}111$ for the British standard cable.

*S.E.T.A.C.**

The working circuit at present used by the British Post Office is similar to the standard common-battery circuit described above, except that the junction is a non-reactive artificial line having a characteristic impedance $Z_0 = 600\ \underline{/0°}$. This artificial line is composed of π sections, the resistances required for various attenuations being given in the Table.

decibels	r	g	decibels	r	g
0·5	8·632	10 417	5·0	84·04	986·9
1·0	17·25	5 201	10·0	155·8	421·6
1·5	25·8	3 450	15·0	209·4	220·5
2·0	34·39	2 583	20·0	245·4	121·2
2·5	42·9	2 052	25·0	268·2	67·6
3·0	51·29	1 703	30·0	281·6	37·99
3·5	59·58	1 450			
4·0	67·8	1 256			
4·5	75·9	1 108			
5·0	84·04	986·9			



It is proposed to eliminate the supervisory relay and increase the p.d. of the operating battery to 24 volts. The future working circuit of the British Post Office will incorporate these modifications and will then be known as S.E.T.A.C., in order to comply with the suggestions of the C.C.I. The equivalent circuit of the S.E.T.A.C., together with various useful impedances, are given in Appendix II.

As regards condition 2, the microphone is always tapped before a speaker commences testing.

In order that the position of the mouth relative to the mouthpiece shall be the same for each speaker, a suitable wire guard is fitted at the front. In the case of pedestal instruments this consists of a wire ring 1 inch in diameter, fixed in the centre of the plane of the flare of the mouthpiece. When testing hand micro-telephones this ring is fixed with its centre at the most usual position of the mouth in practice. This position is known as the "modal position" and was determined from measurements on a very large number of heads. The position is fixed from Fig. 19. The plane of the ring is perpendicular to the modal direction in this case.

To determine a speaker's volume some integrating instrument is required which will make allowance for the silent intervals occurring in speech. Two such instruments are described below.

Measurement of Speech Volume.

(1) The instrument recommended by the C.C.I. is described by Sivian† as follows:—"Essentially it is a vacuum-tube rectifier with a rapid-action d.c. meter in the plate circuit. It is operated on a part of the characteristic such that the rectified plate current is roughly proportional to the square of the speech voltage. The

* Système Étalon de Travail utilisant des Microphones à charbon.
† See Bibliography, (23).

rectifier is preceded by an amplifier of adjustable gain. For the speech-level under measurement the gain is adjusted to such a value that the fluctuating meter deflections attain a prescribed maximum value on the average of once in about three seconds. That value of gain expressed in decibels with respect to a certain normal value of gain gives the volume indicator measure of the speech-level. The meter, combined with the electric circuit, has a dynamic characteristic as shown in the curve, Fig. 20, which gives the maximum deflection as

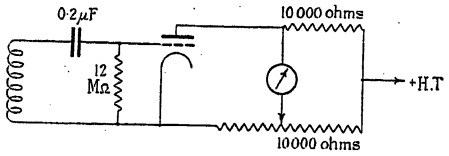


FIG. 21.—Rectifier circuit for speech meter.

a function of the duration of the a.c. input. For inputs lasting more than about 0·18 second the maximum deflection remains the same. Since the average syllable duration is of the order of 0·2 second, it follows that the maximum deflection of the 'volume indicator' is approximately proportional to the mean power of the syllable." The volume indicator is thus a type of valve voltmeter. It is calibrated with alternating current at a fixed frequency of 1 000 cycles per sec.

(2) An alternative method of measuring speech volume has been devised in the Research Section of the British Post Office. This is by means of a "speech meter," which is similar in performance to the "impulse meter" used in Germany and described by Thierbach.* Unlike the volume indicator, it has its own microphone, which is a condenser microphone fitted with a suitable guard. This consists of a wire ring 4·7 cm outside diameter with its plane parallel to and concentric with the diaphragm and at a mean distance of 4·1 cm from it. Speech from the microphone is amplified by means of a screened 2-stage resistance-capacitance-coupled amplifier, the output from this being transformer-coupled to the grid-leak rectifier shown in Fig. 21.

A bridge arrangement is used in the anode circuit of the rectifier to eliminate the normal anode current from the milliammeter. With the valves, condenser, and grid leak used, the needle reads within 2 decibels, i.e. 80 per cent of full-scale deflection 0·2 second after switching on a steady tone, and it falls to zero in 2 seconds after the tone is switched off. Three arrangements have been tried: (*a*) As above, (*b*) with both times increased 3-fold, and (*c*) with both times increased 6-fold. A similar performance is obtained in the three cases with speech, except that in (*b*) and (*c*) the speech must be continued for a longer period, although the deflection of the instrument is much steadier.

The instrument is entirely mains-operated, the necessary h.t. supply being obtained from metal rectifiers. The valves used are of the remote-heated cathode type.

With reference to (4), pedestal instruments are usually tested with the diaphragm of the microphone in the vertical plane, the position for that of the hand microtelephone being 15° to the vertical.

Standard Carbon Microphones.

When testing microphones on the above circuits, comparison is made with a standard carbon microphone. This microphone is one of a number of working standards. These working standards are checked periodically against a number of standards of similar type which are retained for the purpose of calibration only. All these standards are treated with the utmost care and, when not in use, are kept in a standards room at constant temperature. Previously, the efficiencies of the carbon standards were obtained by an elaborate method of cross-checking, and, although this method gave the relative efficiencies of the instruments, yet a drift in the efficiencies of all the microphones could not be observed. However, since the efficiencies of new supplies of the same type of microphone were all of the same order year to year, it can be safely assumed that no serious drift in efficiency took place. It will be seen, nevertheless, that a need of reference to some absolute standard really existed. This has now been made possible by the setting-up of a master reference system in the laboratories of the C.C.I. in Paris, the system being capable of calibration by electro-acoustic methods.

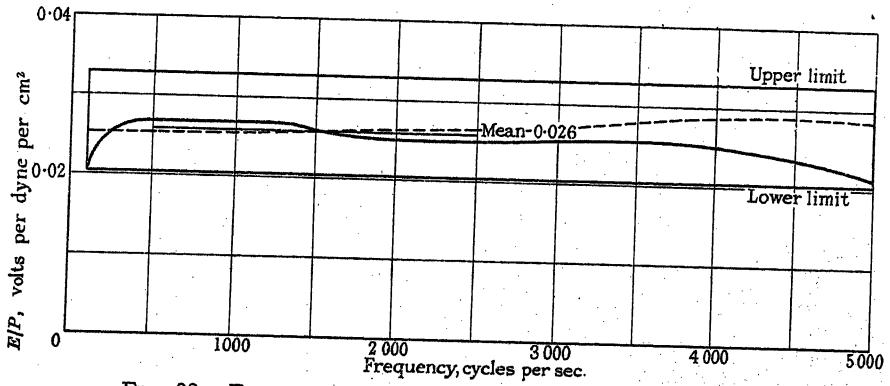


FIG. 22.—Frequency characteristic of microphone and amplifier.

Full curve—British primary standard.
Broken curve—S.F.E.R.T.

* See Bibliography, (24).

S.F.E.R.T.

The master reference system referred to above is known as the S.F.E.R.T.* It is a replica of the master reference system of the Bell Laboratories, New York, and has been fully described by Martin and Gray.† Essentially it consists of a high-quality transmitter, non-reactive artificial line, and high-quality receiver, with the necessary apparatus for calibration.

The microphone used is a condenser microphone of the Wente type with a 4-stage resistance-capacitance-coupled amplifier. The gain of the amplifier is set so that the overall performance is in accordance with Fig. 22. The mean numeric for a range of frequencies 500 to 2 500 cycles per sec. is 0·026 volt per barye,* when the acoustic pressure on the microphone diaphragm is supplied by a thermophone as previously mentioned. The amplifier is capable of adjustment in steps of 0·2 decibel. It is interesting to note that the output from a solid-back carbon microphone equal in efficiency to the Department's standard, working on a zero-ohm local line into a non-reactive impedance of 600 ohms, is 1·3 volts with normal speech. Assuming that normal speech creates an acoustic pressure of 30 dynes per cm² on the microphone diaphragm, the numeric in this case is 0·0434 volt per barye, indicating that the Department's standard is of the order of 4·5 decibels better than the undistorted S.F.E.R.T.

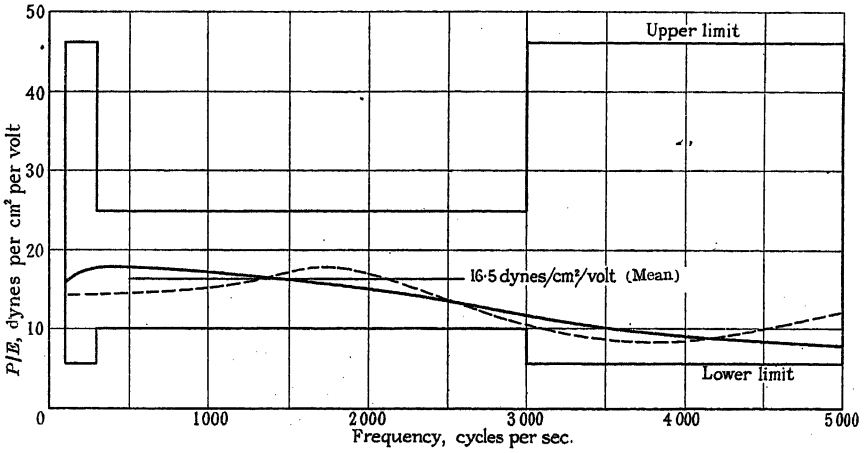


FIG. 23.—Frequency characteristic of receiver and amplifier.
Full curve—British primary standard. Broken curve—S.F.E.R.T.

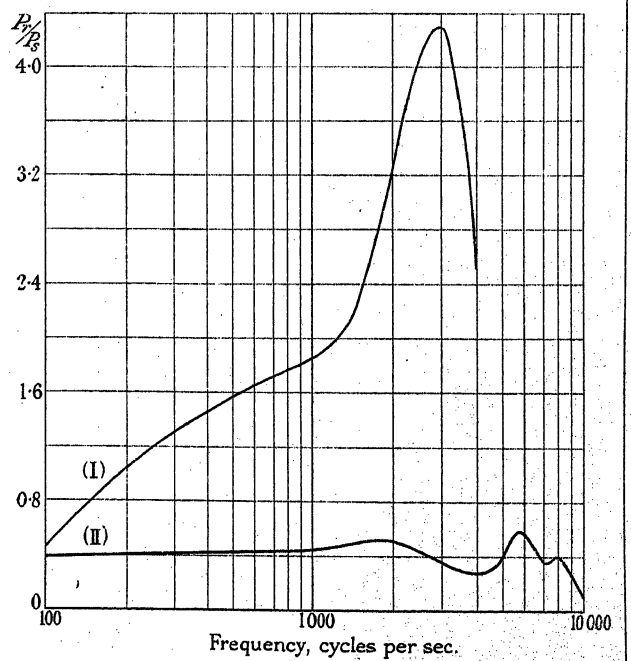


FIG. 24.—Overall frequency characteristic of S.F.E.R.T. microphone, receiver, and amplifiers.
Curve (I) { Microphone—Free-air calibration. Receiver—Artificial-ear calibration.
Curve (II) Paris calibrations.

The output impedance of the microphone amplifier is $600\angle 0°$, the permissible range in modulus being 570–630 ohms and that of the argument $\pm$ 10°.

The non-reactive artificial line has a characteristic impedance of $600\angle 0°$ and an attenuation of 24 decibels.

The receiver consists of a 3-stage resistance-capacitance amplifier, having an input impedance of $600\angle 0°$, with the same limits as for the microphone amplifier, operating a high-quality moving-coil receiver. The performance of the receiver and amplifier is shown in Fig. 23, the numeric over a frequency range 500 to 2 500 cycles per sec. being 16·5 baryes per volt. It will be seen, therefore, that over this frequency range the overall performance of the S.F.E.R.T. with zero junction is 0·43 barye/barye, i.e. an overall attenuation of 7·34 decibels.

The microphone and receiver amplifiers of the S.F.E.R.T. are capable of being distorted, in order that their frequency characteristics should be similar to those of a commercial transmitter and receiver respectively, thus eliminating tone difference to a large extent when testing such instruments. However, this has

* Système Fondamental Européen de Référence pour la Transmission Téléphonique.
† See Bibliography, (25).
* 1 barye = 1 dyne per cm².

been found to introduce errors when testing different types of carbon microphones, and for the time being its use has been suspended. The overall frequency characteristics of the S.F.E.R.T. with a zero junction obtained by using different methods of calibration of the instruments are reproduced in Fig. 24. The differences which occur are surprisingly great, and it would appear that considerable investigation is required before the actual characteristic of the circuit in voice-ear tests can be ascertained. It is probable that this performance is between curves (I) and (II) in Fig. 24, firstly since the presence of the microphone will modify the distribution of the sound field, and secondly since the acoustic impedance on the receiver is that of the human ear. This will not necessarily be the same as that due to the artificial ear described in Part I, which was designed on measurements made with ears pressed to the standard earcap.

The Primary Standard Circuit of the British Post Office.

The reference circuit which has been adopted by the British Post Office as primary standard is similar to the S.F.E.R.T. in principle but does not incorporate the calibrating arrangements for the microphone and receiver. The general lay-out of the circuit can be gathered from Fig. 25. The microphones and receivers used are similar to those of the S.F.E.R.T. and are calibrated periodically by the methods described in Part I. Occasionally they are sent to the C.C.I. laboratories in Paris for thermophone calibration. The latter calibration is used for determining the necessary gain of the associated amplifiers, in order to ensure that the

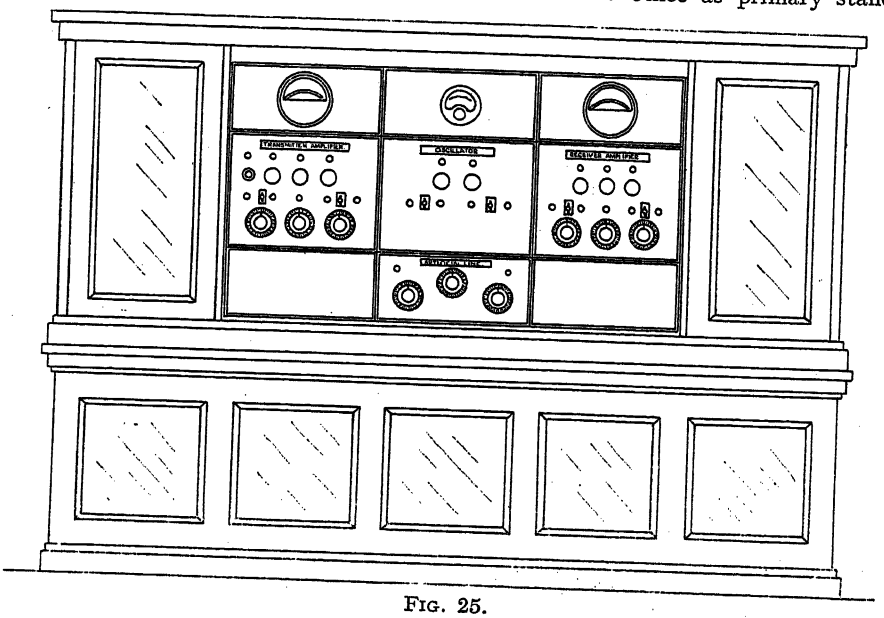


FIG. 25.

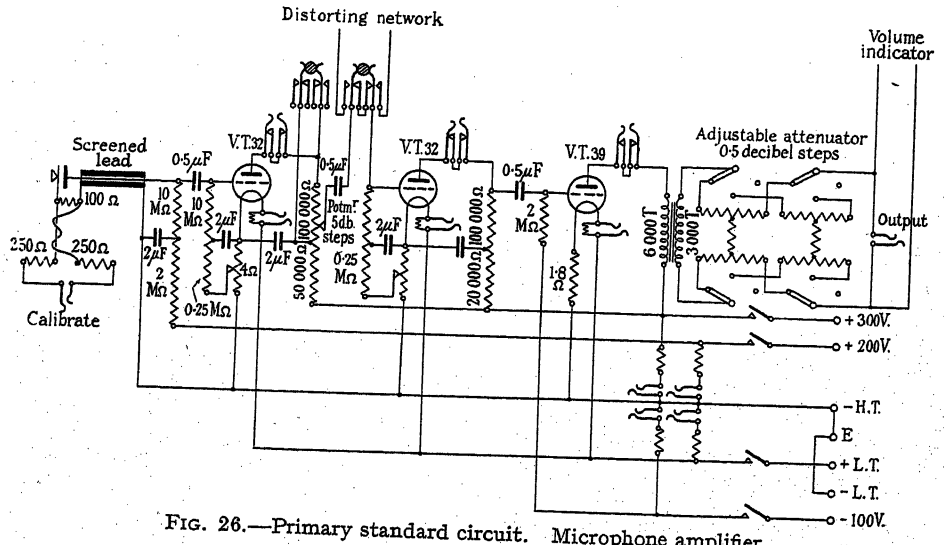


FIG. 26.—Primary standard circuit. Microphone amplifier.

performance of the complete circuit shall be the same as that of the S.F.E.R.T. The British electro-acoustic

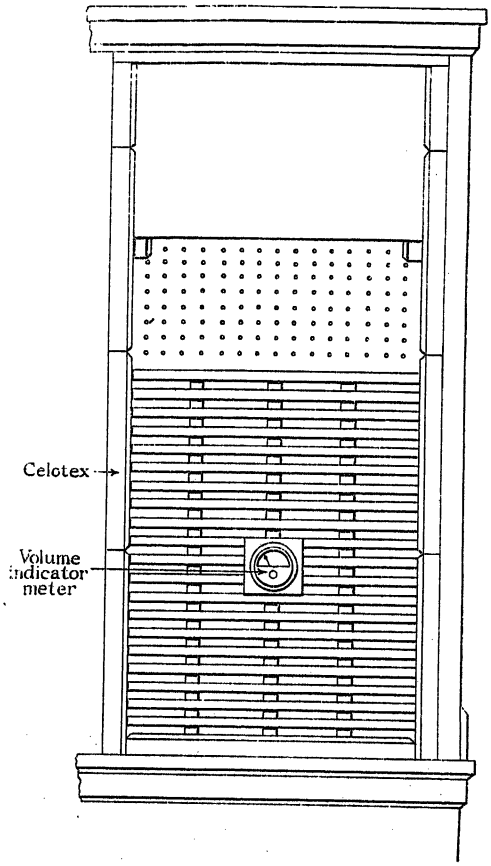


FIG. 27.—Sending booth.

calibrations serve to detect any change which may have occurred in the instruments.

and is capable of adjustment in steps of 0·5 decibel. The combined frequency characteristic of the microphone and amplifier has been included in Fig. 22. A volume indicator similar to the one recommended by the C.C.I. is connected across the output of the microphone amplifier, its instrument being fitted in the microphone cabinet. This cabinet is lined with celotex to minimize reflection, as indicated in Fig. 27. Thus the microphone is spoken into under conditions which are similar to those in open air, and extraneous room noise is considerably reduced.

The receiver amplifier is also 3-stage resistance-capacitance coupled, as will be seen in Fig. 28. Its voltage gain, expressed in decibels, is of the order of zero. The combined frequency characteristic of receiver and amplifier has been added in Fig. 23. The receiving-end cabinet includes a S.E.T.A.C.

Arrangements are included so that distorting networks similar to those used on the S.F.E.R.T. can be connected in the microphone and receiver amplifiers, not necessarily for the purpose of reducing tone difference in volume-efficiency measurements but for comparative articulation tests. Associated with each amplifier is a milliameter by means of which anode and filament currents and voltages, and grid voltages, can be checked, suitable shunts and series resistances being incorporated in the amplifiers themselves.

Routine calibration of the amplifiers is carried out twice daily by means of a valve oscillator and a.c. microammeter. The frequency of the oscillator is 800 cycles per sec., although this will probably be increased to 1 000 cycles per sec., and the output waveform is purified by a balanced 4-section low-pass filter. The output of the oscillator is approximately 1 volt across an impedance of $600\angle 0°$. The output impedance of the oscillator is also $600\angle 0°$, and the a.c. microammeter is arranged to have the same impedance. The circuit of the oscillator is shown diagrammatically in Fig. 29.

To calibrate the microphone amplifier, the oscillator

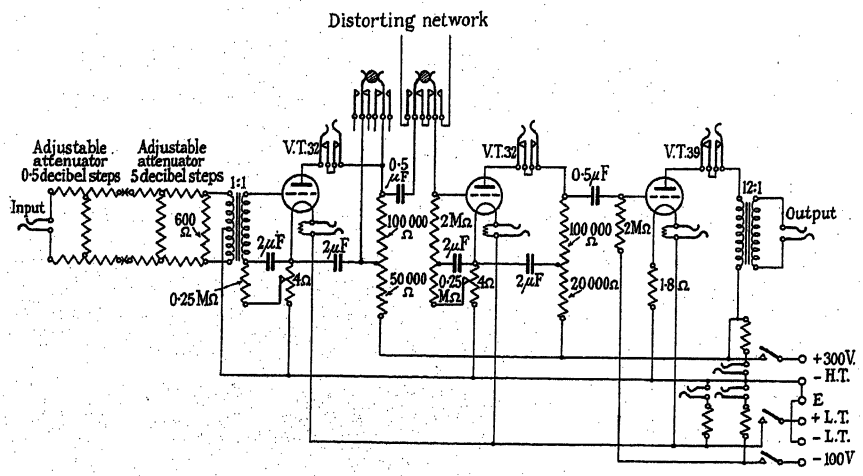


FIG. 28.—Primary standard circuit. Receiver amplifier.

The microphone amplifier is 3-stage resistance-capacitance coupled and is wired in accordance with Fig. 26. It has a gain of approximately 18·5 decibels is connected to an impedance of $600\angle 0°$. The p.d. across a definite fraction of this is impressed on the amplifier in series with the microphone. The output

from the amplifier is connected via the non-reactive artificial line to the a.c. microammeter. The line is set so that its attenuation, together with the attenuation introduced by tapping-off a fraction of the oscillator output, are equal to the required gain of the amplifier, and the amplifier attenuators are then adjusted until

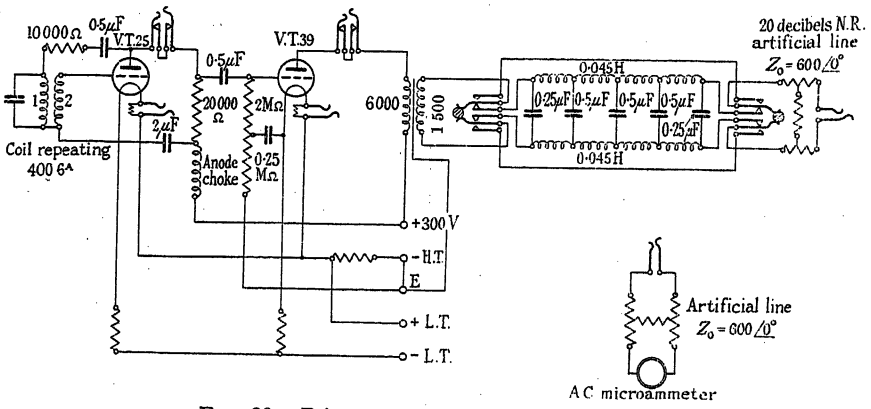


FIG. 29.—Primary standard circuit. Oscillator.

the reading on the microammeter is the same as when the oscillator is connected to it direct.

The receiver amplifier is calibrated in the following manner. The output from the oscillator is connected via the non-reactive artificial line to the amplifier, and the a.c. microammeter is joined across the output, the receiver being in circuit. The length of line is set to the gain required of the amplifier, and then the amplifier

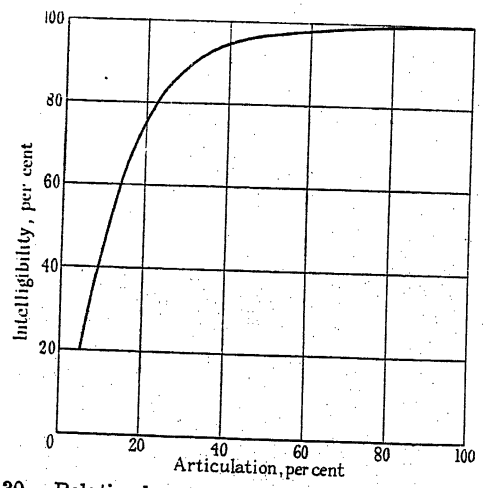


FIG. 30.—Relation between articulation and intelligibility.

attenuators are so adjusted that the reading on the microammeter is the same as that obtained with the oscillator direct. In this case the a.c. microammeter is used as an a.c. voltmeter, but the error introduced thereby is only 0·1 decibel, since the impedance of the receiver is about 20 ohms.

Receivers.

Volume-efficiency measurements on receivers are carried out on the same circuits as those used for microphones, comparison being made with working standard receivers. The efficiencies of these are obtained from tests against receivers of the same type, which are reserved for calibration purposes only. As with standard carbon microphones, these receivers are carefully treated and stored in the standards room. Before the introduction of the primary standard circuit, the efficiencies of these standards were obtained periodically by various cross-checking methods.

Methods of Balancing.

There are at present two distinct methods by which voice-ear tests, for obtaining volume-efficiency measurements, are carried out. In the first, which has been standard practice in England for a considerable number of years and was universally used until recently, three observers—A, B, and C—are required. Hence, six different speaker-listener combinations can be obtained, viz. A-B, B-A, A-C, C-A, B-C, and C-B, so that the result of

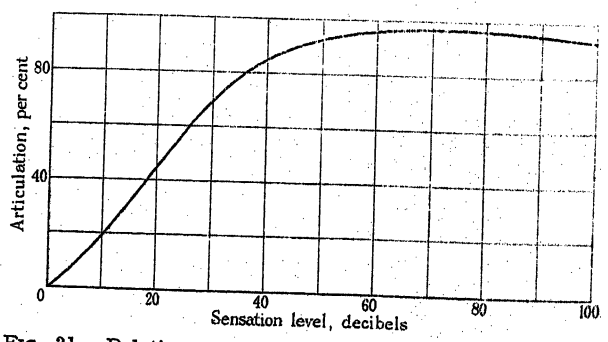


FIG. 31.—Relation between articulation and intensity of received speech.

one complete test is the mean of six distinct observations. Suppose that comparison between two carbon microphones is being made on the standard common-battery circuit and that A is speaking to B. Having tapped the microphones and adjusted his volume to the correct level by means of a volume indicator associated with the circuit or a speech meter, A counts "1, 2, 3, 4, 5," first into the test microphone and then into the standard microphone. When B signals his verdict (test in terms of standard) C's duty is to vary the balancing length of

artificial cable (see Fig. 17). Arrangements are made so that this balancing length can be thrown by C at will in series either with the test or with the standard. In order that the listener shall be on the alert, a reversing key is introduced so that when testing microphones the operation of the whole circuit can be reversed unknown to him. It will be seen that in the above method each observer has only one duty to perform at any one time and is thus able to concentrate on this, with the result that a more careful test can be made.

The second method is used in America and is at present being tried in the Research Section of the British Post Office. Only two observers are required, the listener making his own balance. To eliminate the possibility of his guessing the correct balance from the results of previous observations, a length of artificial cable known only to the speaker and changed at the beginning of each observation is connected in circuit with the standard, the listener's adjustable cable being in series with the test (or vice versa). This method is cheaper than the former and it is claimed that equally reliable results can be obtained in less time. However, it would appear that there is far more strain on speaker and listener.

S	O	NK
T	Ĭ	SH
N	EE	ND
—	E	NT
Z	O	P
N	E	NG
M	OA	T
R	Ĭ	FT
D	O	L
S	AI	Z
—	O	N
T	AI	ST
W	OA	ND
V	E	NJ
GR	A	F
R	EW	SH
R	U	T
D	Ī	NS
N	Ī	N
L	ER	NG
L	A	Z
M	EE	K
L	A	—
S	AI	V
N	Ī	ST

KEY.

Ĭ	as in sit
Ī	,, ,, site
O	,, ,, not
OA	,, ,, boat
A	,, ,, mat
AI	,, ,, bait
E	,, ,, met
EE	,, ,, meet
U	,, ,, cut
EW	,, ,, newt
OR	,, ,, port
ER	,, ,, pert
OU	,, ,, pout
AR	,, ,, part
o͝o	,, ,, book
o͞o	,, ,, moon

T	A	TH
T	EE	V
K	A	—
W	EE	L
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—	OU	—
PR	Ĭ	Z
B	E	L
Y	AR	V
S	E	D
P	Ĭ	N
R	Ī	K
P	EE	SH
S	I	NG
T	OR	Z
T	O	NT
M	Ĭ	Z
K	OU	Z
T	ER	T
F	O	K
M	OR	N
S	ER	N
K	OA	MP
B	ER	NT
W	E	NS

FIG. 32.

Intelligibility and Articulation.

The *intelligibility* of a circuit can be defined as the percentage of ideas correctly transmitted over the circuit. The *articulation efficiency* of a circuit is defined as the percentage of meaningless monosyllables correctly transmitted. The relationship between intelligibility and articulation has been found to be given by the curve in Fig. 30.* Both are functions of the frequency characteristic, the air-to-air attenuation, and, to some extent, the amplitude characteristic of a circuit. The effect of attenuation on articulation will be appreciated by reference to Fig. 31.† Articulation measurements on carbon microphones and commercial receivers are made on the standard working circuit used for volume-efficiency measurements, comparison being made with standard microphones and receivers. The articulation efficiency of the test is given as a percentage of that obtained with the latter. Since the mean level of the received speech on the circuit used is of the order of 50 decibels above threshold, it will be seen that from the attenuation point of view this circuit is ideal, a change of $\pm$ 6 decibels having little effect on the articulation efficiency. In order to reduce the time taken for a complete test with three observers, four receivers are joined in series-parallel, thus enabling two listeners to observe simultaneously, and yet maintaining the electrical conditions as far as impedance matching is concerned.

The actual monosyllables or logatoms used for articulation testing in the Research Section of the British Post Office are of the consonant-vowel-consonant combination, made up by means of a word-building machine.

* See Bibliography, (26). † *Ibid.*

There large brass wheels carry type on their periphery. The frequency of occurrence of the various sounds corresponding to the type has been arranged to be approximately the same as their occurrence in actual speech. The wheels are rotated at different speeds by a friction drive and, by pressing a key, the wheels are disengaged from the drive, stopped, and the letters in a certain position are printed on a strip of paper by

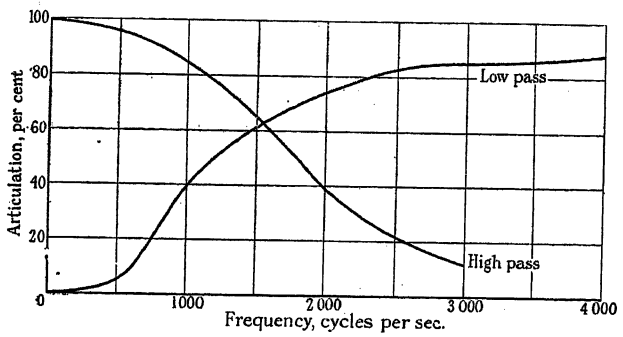


FIG. 33.—Effect on articulation of eliminating certain frequency bands.

means of a typing ribbon. A typical list of syllables so obtained is given in Fig. 32, together with a pronunciation key.

It will be evident that a practice effect will enter into the results from any particular observers. Thus, an inexperienced testing crew will obviously give far lower figures than a highly trained crew. In order to quote

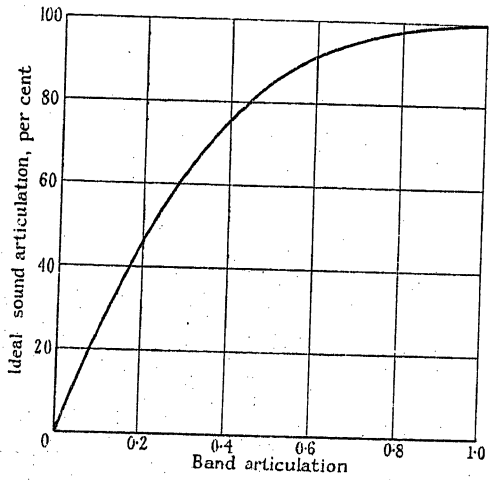


FIG. 34.—Relation between band articulation and ideal sound articulation for English speech.

the articulation efficiency of a particular instrument correctly, the results obtained by the two crews above must be converted to a common figure. Two methods for doing this are at present being investigated by the C.C.I. A brief description of these methods follows:—

(1) *The British Method.*

This is due to Collard, of the I.T. and T. Laboratories.* By this method articulation efficiencies obtained by any crew are converted to the figure which would have been obtained by an ideal crew.

From an examination of the oscillograms* and curves similar to those given in Fig. 33,† for the sounds occurring in speech, Collard has stated that each sound is composed of one or more characteristic frequency bands and that the sounds are recognized by these bands. Having determined the number of bands, the mean frequency, and the level of these bands for all the sounds occurring in a language, it has been found possible to calculate the curve in Fig. 34, which gives the relationship between band articulation, b, and ideal sound articulation for the language. Band articulation is

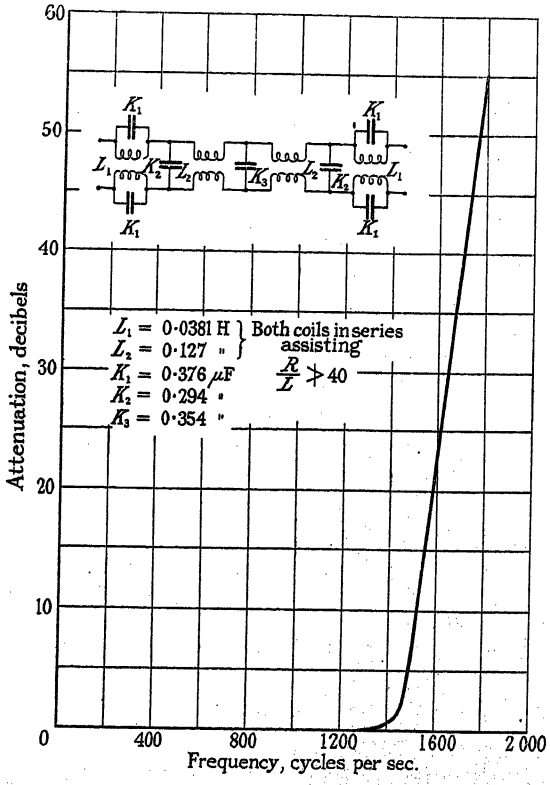


FIG. 35.—Characteristic of low-pass filter. Nominal cut-off = 1 500 cycles per sec.; Z_0 = 600 ohms; m = 0·6.

defined as the average probability that a characteristic band will be correctly received. Thence, from Fig. 33, the band articulation, Δb, contributed to the whole by each 100-cycle frequency band in the speech range has been obtained. The average probability of receiving a frequency band correctly will depend on the level of this band above mean threshold, and hence, for a particular circuit, if the level of each 100-cycle band can be determined and if Δb is known for each band, the total band articulation, $b = \Sigma p \Delta b$, and, therefore, the ideal sound articulation of the circuit, can be calculated, p being the number of speech components within the band which are above threshold. This has been done in Appendix III for a solid-back and a new hand micro-telephone carbon microphone when operating on a high-quality circuit, the minimum air-to-air attenua-

* See Bibliography, (27) and (28).

* See Bibliography, (29). † *Ibid.*, (26).

tion being assumed to be 30 decibels and the attenuations introduced by the microphones having been calculated from the curves in Fig. 7. The ideal sound articulation

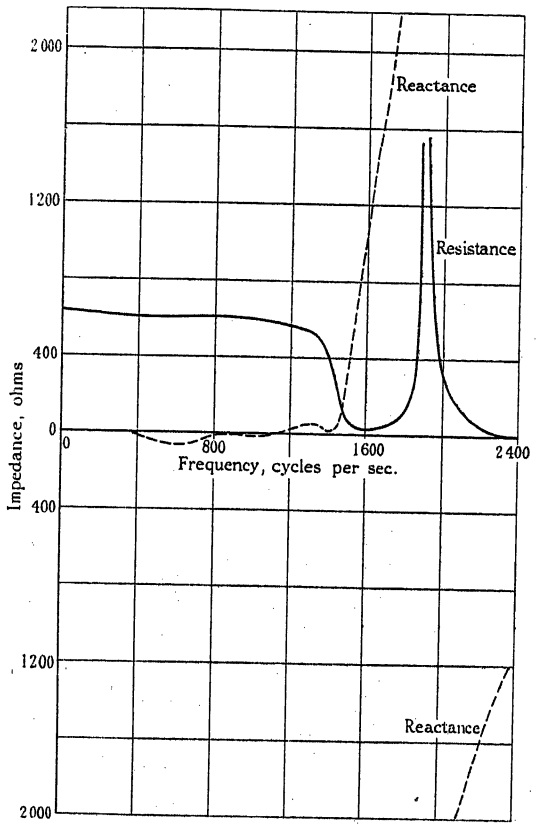


FIG. 36.—Impedance of low-pass filter.
Nominal cut-off = 1 500 cycles per sec.; Z_0 = 600 ohms; terminated by 600 /0°.

of the new hand micro-telephone is in this case 90 per cent, as compared with 63 per cent for the solid-back type. These results agree very well with speech.*

sponds to a band articulation of b', then the crew factor z is given by b/b'. If the crew then obtain an articulation efficiency of a'' per cent, corresponding to a band articulation of b'' on a particular circuit, the ideal sound articulation for this circuit is given by the value corresponding to zb'' in Fig. 34.

A suitable circuit for crew calibration is the undistorted S.F.E.R.T. in which is included a low-pass filter cutting off at 1 550 cycles per sec. Details of a suitable filter are given in Figs. 35 and 36, together with its attenuation and impedance characteristics. The band articulation with this filter is 0·55.

(2) *The American Method.**

By this method the articulation efficiency obtained by a particular crew is converted to that which would have been obtained by an average crew. It has been found that the articulation efficiencies obtained by a particular crew on the same circuit at different periods of its training, or by two different crews on a number of different circuits, when plotted against each other result in a curve of the form

$$1 - A_1 = (1 - A_2)^x$$

where A_1 and A_2 are the corresponding articulation efficiencies obtained, and x is a constant. Thus, to calibrate a crew it is only necessary for it to make a test on a circuit on which the articulation efficiency of the average crew is known, and substitute in the above equation to determine x. The particular circuit suggested is the S.F.E.R.T. with various distortions. The efficiency for the average crew has still to be determined.

Side-tone.

Side-tone in a telephone instrument may be defined as the volume of sound which is heard in the receiver of the instrument due to sound input to the microphone of the same instrument. The effect of excessive side-tone in an instrument is twofold. In the first case, it is a real source of annoyance to the speaker. He will hear room noise in his receiver as well as speech from

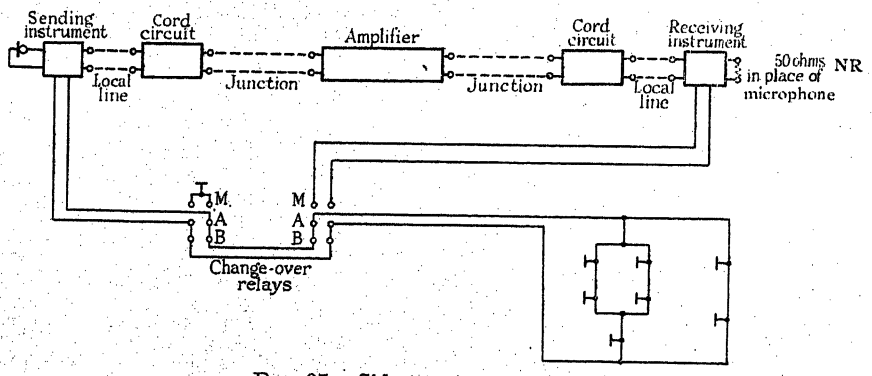


FIG. 37.—Side-tone measurement.

In order to calibrate an articulation-testing crew, all that is required is a testing circuit of which the value of b is known. Suppose that, using this circuit, the crew obtain a sound articulation of a' per cent, which corre-

* See Bibliography, (31).

the other end of the circuit, and, if the former is comparatively loud, connected conversation will be impracticable in a number of cases. Secondly, it causes the speaker to talk at a lower level in order to reduce the

* See Bibliography, (30).

annoyance due to his hearing his own speech. This will degrade his sending efficiency. As a result of a preliminary investigation it has been found that a reduction in the amount of side-tone in the receiver of the new hand micro-telephone by approximately 9 decibels has the effect of causing the speaker to increase his volume by approximately 3 decibels. An ideal state is reached when the side-tone is of the same level as the sound heard in the free ear, although this is governed to a large extent by the location of the instrument.

The circuit used in the Research Section of the British Post Office for measuring the side-tone from telephone instruments is shown diagrammatically in Fig. 37, and details of the amplifier in this circuit are given in Fig. 38. The gain of the amplifier, which is 2-stage, is approximately 36 decibels. Routine gain measurements are made in the following manner:—An a.c. potential difference of approximately 1 volt at 800 cycles per sec.

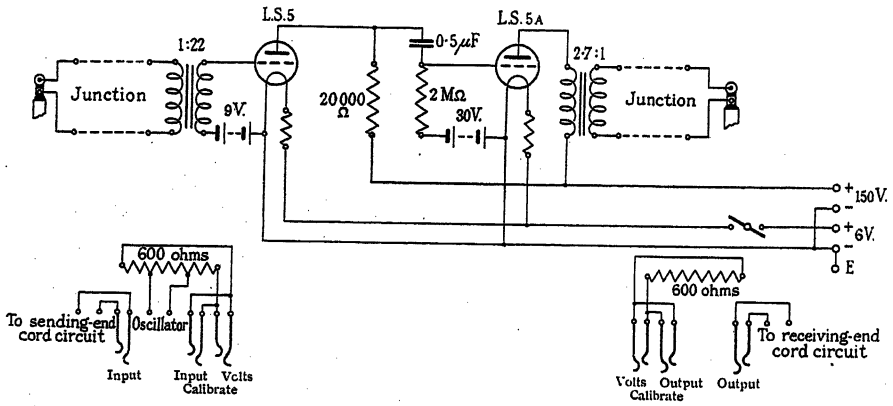


FIG. 38.—Side-tone measurement. Amplifier.

is applied across the input of the non-reactive artificial line which precedes the amplifier. The attenuation due to both pads of artificial line is then adjusted so that the same p.d. is obtained at the output of the artificial line which immediately succeeds the amplifier, when this is closed by its characteristic impedance. The voltage measurements are made by means of a Moullin voltmeter.

The method of reducing the volume of sound in the listening receiver is by the series-parallel arrangement shown, the impedance of the combination remaining approximately equal to that of a single receiver.

The side-tone from the instrument is thus balanced against the output from the circuit direct by varying the length of artificial line in the direct circuit.

This amount of side-tone can be compared with the volume of speech received on any standard circuit, when the following are known:—

(*a*) The gain of the amplifier (p decibels).

(*b*) The equated length above (q decibels).

(*c*) The sending allowance of the sending instrument in terms of the standard circuit (s decibels better).

(*d*) The corresponding receiving allowance of the receiving instrument (r decibels better).

If the comparative circuit is the standard working circuit used in the British Post Office, then the side-tone from a particular instrument is

$$\{30 + (p - q) + (r + s)\}$$

decibels louder than the speech received on this standard working circuit, when using instruments equal in efficiency to the Department's standard.

The side-tone from the average common-battery instrument working on a 300-ohm local line is about 37 decibels louder than the standard above. With the new hand micro-telephone fitted with an anti-side-tone transformer No. 35A, which has its primary winding connected directly across the microphone and its secondary across the receiver, the figure is 27·5 decibels when the microphone is spoken into at the modal position.

Since the presence of excessive side-tone has a psychological effect in causing a speaker to reduce his speech volume, effective transmission tests are made on new types of instruments, so that this effect can be appreciated when considering their sending allowances. In these tests the receiver of the instrument under test is held to the speaker's ear when the microphone is being spoken into.

PART 3. MECHANICAL-ELECTRICAL MEASUREMENTS ON COMMERCIAL MICROPHONES AND RECEIVERS.

It has long been the aim of those investigators in telephony who have been particularly concerned with the determination of the volume efficiencies of carbon microphones and Bell receivers by speech, to replace the voice and ear by suitable electrical means in order that the inherent variations among individuals might be eliminated. Moreover, the testing of every instrument in a new batch of supplies by voice-ear methods occupies a considerable amount of time and is comparatively costly. In 1916 a method was suggested by Cohen for testing carbon microphones.* The voice was replaced by a rhythmic tone from a Bell receiver. The fundamental resonance of this receiver was eliminated to a large extent by means of an electrical resonant shunt across the receiver terminals. The

* See Bibliography, (32).

receiver was connected in the secondary circuit of a transformer, which had a rhythmic interrupter, and a suitable battery was connected across the primary. The rhythmic interrupter consisted of a brass wheel 30 cm diameter with its periphery slotted transversely. The slots were filled with mica. The resultant widths of brass and mica increased uniformly round half the circumference from 2 mm and 1·8 mm to 4 mm and 3·5 mm respectively. The wheel made 160 revolutions per minute, and this speed was maintained constant by means of a governor which inserted a resistance in the armature circuit of the shunt driving motor when the speed became too high. The range of frequencies obtained with this arrangement was therefore 600 to 1 200 cycles per sec. This arrangement is still used as the source of the warble tone for the "life testing of carbon microphones." The listener's receiver and ear were replaced by a valve voltmeter, transformer-coupled, the rectifier being carborundum-steel and the instrument a reflecting galvanometer. The microphone under test was compared with a standard carbon microphone, both microphones being connected alternately in the standard common-battery circuit. The receiver was made to howl into the test and standard microphones alternately, and its movement was utilized to make the necessary change-over connections in the circuit. The balancing cable was adjusted until equal deflections were obtained with both microphones.

The rhythmic tone now used is far more complex than the above.* It is obtained by means of a valve oscillator having its anode-circuit inductance tuned by a rotating air condenser. The speed of the condenser is 300 r.p.m. and the range of frequencies 600 to 1 600 cycles per sec. This rhythmic frequency is mixed with a steady frequency of 180 cycles per sec. in a definite proportion and rectified. After rectification the 180-cycle component is filtered out. Thus an alternating current of complex wave-form is obtained, the minimum and maximum frequencies being 420 and 1 780 cycles respectively. (If f is the frequency of the rhythmic oscillator at a particular instant, then the frequencies simultaneously present will be f, $f + 180$, and $f - 180$.) This alternating current is amplified to the correct level and fed into a moving-coil loud-speaker. The mean output from the loud-speaker at the position occupied by the front of the mouthpiece, when testing solid-back microphones, is 30 dynes per cm^2.

Another method of producing the rhythmic howl is at present under investigation. An arrangement of neon lamps is used in which the rotating condenser is not required.

Microphone Measurements.

When testing solid-back carbon microphones the mouthpiece of the microphone is held against a guard in front of the loud-speaker.

For micro-telephones the guard used is some distance further away from the loud-speaker to allow for the position occupied by the mouth when using an instrument of this type. The microphone is connected in its appropriate instrument circuit and is supplied with direct current from a standard common-battery cord circuit via a 300-ohm non-reactive local line. The junction side of the cord circuit is connected to a non-reactive resistance of 600 ohms. The a.c. potential difference across a fraction of this resistance is measured by means of a valve voltmeter which has its frequency characteristic distorted to simulate that of a Bell receiver when held to the average human ear. The voltmeter is of the balanced anode-bend type; balance is obtained by means of a fraction of the p.d. applied to the loud-speaker, the amount being so arranged that with a microphone under test equal in efficiency to the Department's standard, the d.c. voltmeter connected in the anode circuit of the two rectifying valves will give a mid-scale reading. The voltmeter is calibrated as follows:—The rectifying valve and amplifier normally operated by the output from the microphone under test is connected to a second potentiometer capable of adjustment in steps of 2 decibels, the deflections with the corresponding settings of this potentiometer being marked on the scale.

In the actual test on carbon microphones the loud-speaker is operated automatically at intervals of 2 seconds for a period of 2 seconds, the reading during the fifth period being taken. By this means the efficiency of the microphone is measured when it is in an unpacked condition. The resistance of the microphone is measured (with the howl on) immediately afterwards on the same voltmeter by simply operating a key.

By this method about 120 microphones per hour can very accurately be tested for volume efficiency and resistance, as compared with about 60 per hour from two skilled observers by voice-ear tests, in which the degree of accuracy is not so high.

Receiver Measurements.

In order to obtain the efficiency of a receiver by the method described above, the receiver is treated as an alternator. It is fitted with an artificial ear* which carries a mouthpiece, and this mouthpiece is held against the guard used for testing solid-back microphones. A continuous howl is used, since no packing occurs in this instance, and the method of test is very similar to the one described for microphones. As many as 1 900 receivers per day have been tested by one set of apparatus.

The source of supply of the various d.c. voltages for these tests can be either a motor-generator supplying filament and anode voltages or a battery of accumulators charged by rectifiers at night for the filaments and a metal rectifier for the anodes.

Although the method of test described above has been very useful in accepting supplies of solid-back carbon microphones and of the new micro-telephone of a particular manufacture, it must be pointed out that it is still in the development stage, and therefore cannot be used indiscriminately.

"Frying" of Carbon Microphones.

The characteristic "fry" of a carbon microphone is due to sparking and arcing between granules and between granules and electrodes. It is generally more prevalent in high-resistance microphones. This "fry," if present, has the same effect as any other noise in a telephone circuit and reduces the intelligibility of the circuit.

* See Bibliography, (33) and (34).

* See Bibliography, (35).

The amount of " fry " in a carbon microphone is measured by means of a valve voltmeter. This voltmeter is calibrated by means of an artificial " fry," produced in the following manner. A copper disc 9 in. diameter carries 16 4-in. lengths of No. 28 S.W.G. piano wire. The disc is rotated slowly, causing the wires to scratch over a coarse file. This causes an irregular contact resistance between the disc and the file. This contact in series with a suitable battery is connected across the primary circuit of a transformer. The secondary circuit contains a thermo-milliammeter and a resistance of 0·5 ohm. The valve voltmeter is calibrated by the voltage across this resistance.

In the actual measurement, the microphone is joined in the sending-end circuit of the standard common-battery circuit, the local line used being of 35 ohms.

teristics of the terminal apparatus,* the C.C.I. propose that the noise meter shall be connected across the receiver in a subscriber's instrument circuit, which forms part of a circuit model. The model is to be the equivalent of a trunk exchange cord circuit, trunk junction, common-battery exchange cord circuit and a subscriber's local line, all connected in tandem to the subscriber's instrument. Each component is to be the average for the type.

The input impedance of the noise meter is to be not less than 10 000 ohms. The specified frequency/response characteristic is to approximate to the mean curve in Fig. 39 with the tolerances indicated. This characteristic is the inverse of the relative voltages of single-frequency disturbances which will produce an equal loss in articulation efficiency on the above circuit.

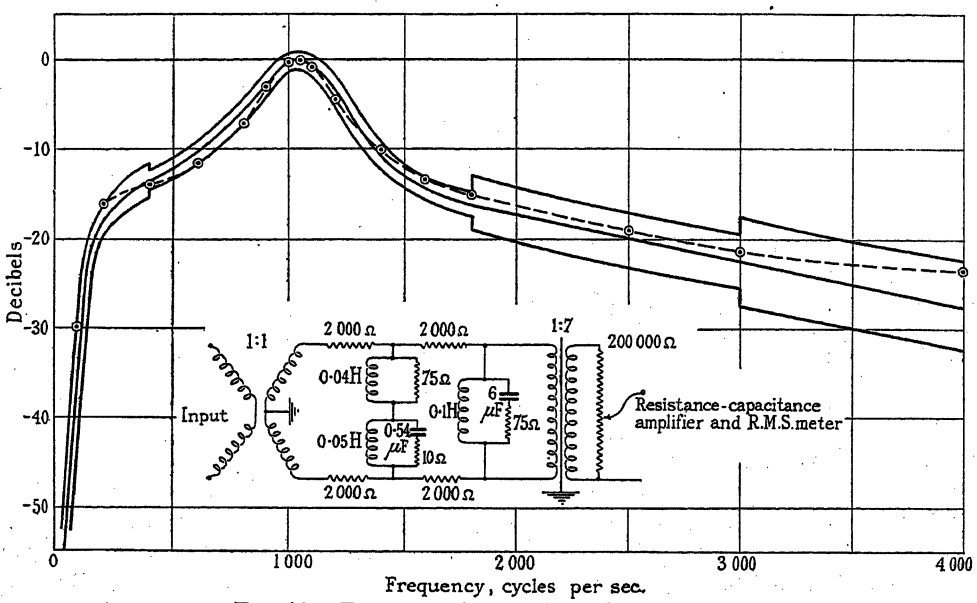


FIG. 39.—Frequency characteristic of noise meter.

——— C.C.I. curve and permissible limits.
--o--o-- British Post Office curve.
For inductances: $R/L \gg 100$.

resistance. The junction is replaced by a non-reactive resistance of 600 ohms. The maximum permissible voltage due to " fry " across this resistance is 0·3 millivolt. The valve voltmeter is actually connected across an impedance which replaces the receiver in the above circuit and is equivalent to the impedance of the latter at 800 cycles per sec. A high-impedance receiver is connected across the 600 ohms so that the noise causing a deflection may be heard. In order to ensure that this measured noise is due to " fry," the measurement is made in a well-silenced cabinet.

It is highly probable that a noise meter which has a performance similar to that recommended by the C.C.I. for the measurement of noise on telephone lines, will shortly be used to measure the amount of " fry " from carbon microphones.

The C.C.I. Noise Meter.

Since the effect of noise induced on a telephone line will depend on the impedance and attenuation charac-

It will be observed that the peak is at the frequency of the fundamental resonance of the receiver, when held to the ear. (The frequency characteristic of the meter suggested for determining the amount of noise on radio circuits is much flatter than the above.)

The instrument is to record the R.M.S. value of the various frequency components in the noise, although the disturbing effect of a noise has probably a value between the mean and R.M.S. values of the components.† The maximum permissible amount of noise has been tentatively fixed at that which will cause a loss in articulation efficiency of 5 per cent. This is of the order of 0·3–0·4 mV at 800 cycles per sec. across the receiver terminals. The noise meter is calibrated by a fixed frequency at 800 cycles per sec., and in order to obtain a measurement independent of the particular receiver used this is multiplied by the factor $\sqrt{(600/Z)}$, where Z is the modulus of the impedance of the receiver. By this means the measured noise is converted to that

* See Bibliography, (36 † *Ibid.*, (37).

which would have existed across a resistance of 600 ohms.

An experimental noise meter on the above lines has been constructed in the Research Section of the British Post Office. The frequency characteristic of this meter has been included in Fig. 39, together with a circuit diagram of the network by which this performance is obtained. The input impedance is greater than 4 000 ohms. The network is connected to a 4-stage resistance-capacitance-coupled amplifier, the output of which operates a thermal milliammeter or, if greater sensitivity is required, a full-wave anode-bend rectifier. A schematic diagram of this rectifier is shown in Fig. 40. The valves selected have similar characteristics and these follow a square law very closely over the required range.

Life Tests on Carbon Microphones.

In order to obtain the effect of practical use on the performance of carbon microphones, selected ones from

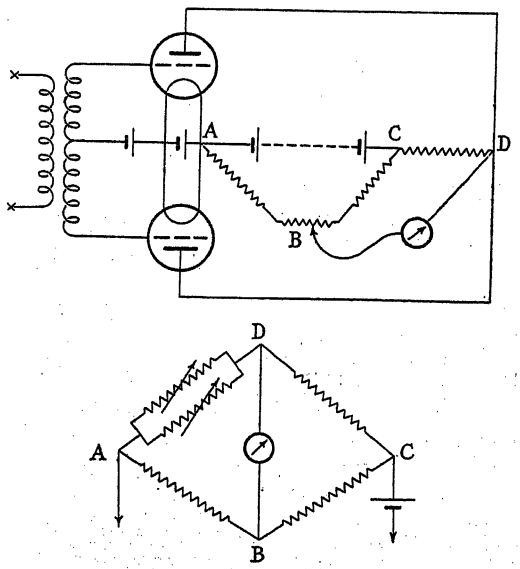


FIG. 40.—Full-wave anode-bend rectifier.

any new type or new supply are submitted to an ageing or life test. The microphones are mounted on vertical rods in a cylindrical tank, the temperature of which can be controlled by means of a thermostat. They are connected in the particular circuit in which it is intended they shall be used, i.e. a common or local battery. The cycle of operations to which the microphones would be subjected in an average call, $1\frac{1}{2}$ minutes in practice, is simulated, the mechanical treatment being replaced by a more or less equivalent electrical effect, as follows:—

(1) Feeding current is switched on, representing the lifting of the receiver from its switch hook by the subscriber.

(2) A klaxon is operated momentarily—this simulates the removal of the receiver by the subscriber.

(3) 7·5 secs. later the microphone is subjected to a rhythmic howl or warble tone for 7·5 secs. This tone is repeated seven times at intervals of 7·5 secs.

(4) At the end of $1\frac{1}{2}$ minutes the current is switched off, the klaxon having previously been momentarily operated.

There is then an interval of $1\frac{1}{2}$ minutes, after which the above cycle is repeated. Assuming that in practice the number of calls per subscriber per year is 3 000, it will be seen that by this means the effect of a year's use on a microphone can be obtained in about a week. Having obtained the volume and articulation efficiencies and the resistance of the microphone before and after this test, an estimate of the suitability of the microphone for service can quickly be arrived at.

Receiver Flux Measurements.

To make these measurements a search coil is connected to a ballistic galvanometer. The galvanometer is calibrated by means of breaking a known current in the primary circuit of a known mutual inductance, the secondary of which is connected to the galvanometer. The search coil used consists of a known number of turns (approximately 200) of No. 47 S.W.G. enamelled copper wire wound diametrically round a slotted diaphragm, the width of the coil being such as easily to clear the pole-pieces of the receiver magnet under test, and the depth being sufficiently small to enable the diaphragm to occupy its correct position. Flux measurements on a Bell receiver are given below, together with other relevant information.

Normal flux = 970 maxwells.
Additional flux due to 25 mA = 82 maxwells.
Reduced flux due to 25 mA = 88 maxwells.
Cross-sectional area of pole-pieces = 0·23 cm².
Normal flux density = 4 210 gauss.
No. of turns on winding = 2 × 605 = 1 210.
Average reluctance at normal flux = 0·45 oersted.
Length of air-gap = 2 × 0·012 × 2·54 = 0·061 cm.
Reluctance of gaps = 0·265 oersted.
Reluctance due to iron circuit = 0·185 oersted.
D.C. inductance of receiver windings = 0·041 henry.
D.C. resistance of receiver windings = 60 ohms.
A.C. impedance at $\omega = 2\pi f = 5\,000$, with testing p.d. of 1 volt, when held to artificial ear = $141 + j141 = 200 \angle 45° = 141 + j\omega 0{\cdot}028$.

Demagnetization of Receiver Magnets.

A receiver magnet is weakened by:—

(*a*) Rough mechanical treatment.
(*b*) A heavy reverse direct current in the windings, and
(*c*) Large alternating currents in the windings.

The effect of the above on any new type of receiver is determined, so that an estimate of its commercial life can be ascertained. The mechanical treatment is applied by suddenly dropping the receiver a distance of about $\frac{1}{4}$ in., 50 000 times, the normal ear-cap being replaced by a similar one made of steel.

The change in flux, after having been subjected to reverse direct currents up to 200 mA for varying lengths of time, is measured. As regards (*c*), the receiver is connected in its normal circuit and an a.c. supply of 80 volts at 16 cycles per sec. is applied to the circuit for a considerable time to determine the effect of ringing current on the receiver magnet.

PART 4. MEASUREMENTS OF THE COMMERCIAL EFFICIENCY OF TELEPHONE APPARATUS.

In certain districts it is now possible to make routine measurements of a subscriber's transmission at his exchange. The instrument used is essentially a valve voltmeter. The rectifier is similar to the one employed in the speech meter, with the exception that the grid leak is connected to the filament of the valve via a relay contact. This relay is very sensitive and is operated by means of an amplifier rectifier from the actual speech currents. Thus, the recording instrument measures the subscriber's volume and its reading is quite steady, since, during an interval, the grid of the rectifying valve remains insulated, and the condenser remains charged to its previous value. If complaints are received of poor transmission or if abnormal transmission is noted in these routine tests, the overall transmission of the circuit is tested as follows:—

A lineman takes a previously calibrated carbon microphone to the subscriber's premises. This is connected across the line with the receiver of the ordinary instrument still on the switch hook, i.e. the 1 000-ohm bell and 2-μF condenser form the only shunt across the microphone. The lineman then counts " 1, 2, 3, 4, 5 " into the calibrated microphone at his normal volume-level. The reading obtained on the valve voltmeter at the exchange is noted. Then, having disconnected the calibrated microphone and removed the receiver from its switch hook, the lineman speaks in the same manner into the subscriber's microphone and the reading on the exchange instrument is again noted. If the loop resistance of the subscriber's line is known, the feeding current to the calibrated microphone can be calculated and its efficiency, when used in the above condition, estimated from the curve shown in Fig. 15. Thus any fault in a subscriber's microphone can be discovered and rectified.

A similar measurement has also been used for determining the efficiency of subscribers' receivers in situ, but since very little trouble is experienced in this connection it has now been discontinued.

An endeavour is at present being made to replace the voice in these tests by a standard noise produced by simple mechanical means.

The above test takes no account of the articulation efficiency and therefore of the intelligibility of the circuit, and it is possible that in certain cases the volume efficiency of a circuit may be normal and yet the circuit may not be commercial. Although the performance of the various instruments, circuits, etc., can be estimated from the measurements previously described in the paper, it is thought that a further means of obtaining their commercial efficiency when in actual use should be developed. A method of obtaining this efficiency is shortly to be put in hand, and series of tests will be made on selected circuits. It is expected that these tests will extend over a period of about three years and that valuable information will be obtained therefrom. The results of these tests will probably be the subject of a later paper.

CONCLUSION.

An attempt has been made to indicate the progress of standardization in recent years of the measurements made on telephone instruments. It will have been appreciated that the subject is one of considerable interest and has many pitfalls.

As an example of the results obtainable from tackling telephone instrument problems on scientific lines, the introduction of the new hand micro-telephone will probably suffice.

Owing to the wide scope of the paper, a considerable amount of interesting detail has perforce been omitted. It is hoped, however, that the Bibliography is sufficiently complete to enable any further information on the subject to be obtained.

Finally, the author desires to express his thanks to the Engineer-in-Chief of the British Post Office for granting permission for the paper to be read, since it includes much official information. Also the author's thanks are due to Captain B. S. Cohen, staff engineer in charge of the Research Section of the British Post Office, and to all other members of the staff of the Research Section, especially the author's colleagues in the Transmission Apparatus group, without whose valuable assistance the preparation of this paper would have been impossible.

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APPENDIX I.

CALCULATION OF CONSTANTS OF TELEPHONE RECEIVER DIAPHRAGM FROM FREQUENCY CHARACTERISTICS.

Total mass of receiver diaphragm $= 3{\cdot}76$ grammes
Radius of receiver diaphragm $= 2{\cdot}62$ cm
Inside radius of clamping ring $= 2{\cdot}38$ cm

Since the diaphragm is clamped at the edge, its motion for frequencies below that of its fundamental mode of vibration can be assumed to be of the form*

$$x = x_0\left(1 - \frac{r^2}{a^2}\right)^2$$

where x_0 = displacement of the centre,
a = inside radius of clamping ring,
and x = displacement at a radius r from the centre.

In this case, the mass of the equivalent piston is

$$\frac{1}{5}\left(\frac{2{\cdot}38}{2{\cdot}62}\right)^2 3{\cdot}76 = 0{\cdot}62 \text{ gramme}$$

Also, since the average displacement of the diaphragm is $\frac{1}{3}x_0$, the equivalent piston area, referred to the motion at the centre, is

$$\tfrac{1}{3}\pi(2{\cdot}38)^2 = 5{\cdot}93 \text{ cm}^2$$

Volume Q of cavity between the diaphragm and standard ear-cap $= 2{\cdot}8$ cm^3

$$\therefore\ K_A = \frac{Q}{\rho C^2}\dagger = 2{\cdot}02 \times 10^{-6}$$

where K_A is the acoustic capacitance of the cavity.

From Fig. 11 (curve B), the resonance frequency of

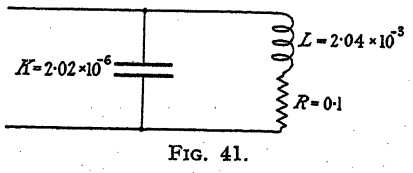


FIG. 41.

this cavity with the acoustical mass at the aperture is 2 480 cycles per sec.

But if m_A is the acoustical mass of the air at the aperture,

$$\omega_0 = 2\pi \times 2\,480 = \frac{1}{\sqrt{(m_A K_A)}}$$

$$\therefore\ m_A = 1/K_A\omega_0^2 = 2{\cdot}04 \times 10^{-3} \text{ gramme/cm}^4$$

As an estimate of R_a, the acoustic resistance of the air in the aperture of the earcap, suppose

$$R_a = \frac{\rho c \omega^2}{3\pi c^2} = 4{\cdot}08\frac{\omega^2}{c^2}$$

As the frequency of fundamental resonance of the diaphragm (see Fig. 11, curve B) is 810 cycles per sec.

$$R_a = 0{\cdot}1 \text{ gramme/cm}^4 \text{ (approx.)}$$

The equivalent electrical circuit for this condition is thus as shown in Fig. 41.

* H. LAMB: "Dynamical Theory of Sound."
† W. WEST: "Acoustical Engineering."

At $f = 810$ cycles per sec. the impedance of this network is practically

$+j11 \cdot 39 = Z_a$ (the acoustic impedance on the diaphragm)

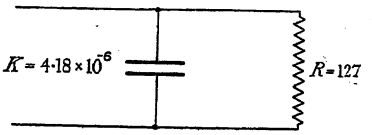


FIG. 42.

The mechanical impedance due to this is $Z_m = (5 \cdot 93)^2 j11 \cdot 39 = j396$, i.e. an added mass of 0·078 gramme.

Now, when the receiver is held to the artificial ear, the acoustic impedance on the diaphragm can be represented as shown in Fig. 42, since, for the artificial ear, $Q = 3$ cm^3, and $R = 127$.

The impedance of this network is, at $f = 1\,060$ cycles per sec., the resonant frequency under this condition (Fig. 11, curve A),

$$Z_A = 9 \cdot 35 - j33 \cdot 2$$

and
$$Z_m = (5 \cdot 93)^2 \{9 \cdot 35 - j33 \cdot 2\} = 327 - j1\,162$$
$$= 327 - j\frac{7 \cdot 75 \times 10^{-6}}{\omega}$$

Thus, the artificial ear adds at this frequency a mechanical resistance $r' = 327$ dynes/cm/sec. and a stiffness $S' = 7 \cdot 75 \times 10^6$ dynes/cm to the diaphragm and removes a mass of $m' = 0 \cdot 078$ gramme.

But from curve B (Fig. 11), for the fundamental resonance,

$f_0 = 810$ and $\Delta = 188$, and from curve A
$f_0 = 1\,060$ and $\Delta = 502$.

Hence, if the equivalent mechanical constants of the receiver diaphragm are:

Resistance = r dynes/cm/sec.,

Stiffness = S dynes/cm (including the stiffness due to the cavity behind the diaphragm), and

Mass = m grammes

then $\dfrac{r}{2(m + 0 \cdot 078)} = 188$, i.e. $r = 376m + 29 \cdot 3$

and $\dfrac{r + 327}{2m} = 502$

$\therefore r + 327 = 1\,004m$

Whence $m = 0 \cdot 567$ gramme

and $r = 263$ dynes/cm/sec.

Again, $\sqrt{\left[\dfrac{S}{m + 0 \cdot 078}\right]} = 2\pi \times 810$

and $\sqrt{\left[\dfrac{S + 7 \cdot 75 \times 10^6}{m}\right]} = 2\pi \times 1\,060$

$\therefore S = 15 \cdot 5 \times 10^6$ dynes/cm

and $m = 0 \cdot 52$ gramme

APPENDIX II.

THE EQUIVALENT CIRCUIT OF THE S.E.T.A.C.

Component (see Fig. 43)	Equivalent	Impedance at $\omega = 2\pi f = 5\,000$
BC	$-M$	$-25 - j439 = 440\angle 93 \cdot 25°$
CA	$P + M + R + 2\mu F$	$214 + j861 = 888\angle 76°$
CD=NO	$S + M$	$70 + j973 = 975\angle 85 \cdot 9°$
DE=MN	—	$300\angle 0°$
EF=LM	$P - M$	$39 \cdot 5 - j23$
FA=LA	$+M$	$40 + j1\,760 = 1\,761\angle 88 \cdot 7°$
FG=KL	$S - M$	$39 \cdot 5 + j63 = 74 \cdot 3\angle 58°$
GH=HK	—	$563 \cdot 2\angle 0°$
HA	—	$37 \cdot 99\angle 0°$
OP	$r - M$	$25 - j439 = 440\angle 86 \cdot 75°$

At $\omega = 2\pi f = 5\,000$:—

Impedance measured across junction side of repeating coil = $660\angle 37 \cdot 2°$.

Impedance measured across transmitter terminals = $216\angle 22 \cdot 3°$.

Impedance measured across receiver terminals = $322\angle 36 \cdot 3°$.

Insertion loss due to 30 decibels of non-reactive artificial line = 29·6 decibels.

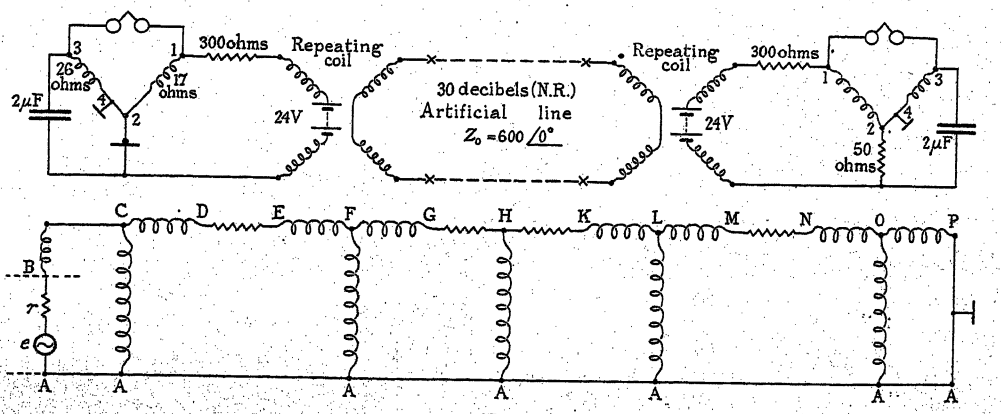


FIG. 43.

APPENDIX III.

Hand Micro-Telephone Microphone.

Frequency range	Normal air-to-air attenuation of circuit	Attenuation due to microphone	Total attenuation of circuit	Mean speech level above threshold	Level of received speech above threshold	p	Δb	$p\Delta b$
cycles/sec.	decibels	decibels	decibels	decibels	decibels			
500–600	30	18	48	80	32	0·99	0·06	0·0594
600–700	30	16	46	82	36	1·0	0·055	0·055
700–800	30	15	45	85	40	1·0	0·045	0·045
800–900	30	14	44	86	42	1·0	0·04	0·04
900–1 000	30	13	43	87	44	1·0	0·036	0·036
1 000–1 100	30	11	41	88	47	1·0	0·032	0·032
1 100–1 200	30	9	39	88	49	1·0	0·029	0·029
1 200–1 300	30	6	36	88	52	1·0	0·027	0·027
1 300–1 400	30	2	32	87·5	55·5	1·0	0·025	0·025
1 400–1 500	30	—	30	87	57	1·0	0·022	0·022
1 500–1 600	30	2	32	86	54	1·0	0·021	0·021
1 600–1 700	30	4·5	34·5	85	50·5	1·0	0·019	0·019
1 700–1 800	30	5·5	35·5	84	48·5	1·0	0·018	0·018
1 800–1 900	30	6·5	36·5	82	45·5	1·0	0·017	0·017
1 900–2 000	30	7·0	37	80	43	1·0	0·016	0·016
2 000–2 100	30	6·0	36	78	42	1·0	0·015	0·015
2 100–2 200	30	4·5	34·5	76	41·4	1·0	0·014	0·014
2 200–2 300	30	4·0	34	75	41·0	1·0	0·013	0·013
2 300–2 400	30	4·5	34·5	74	39·5	1·0	0·012	0·012
2 400–2 500	30	6	36	73	37	1·0	0·012	0·012
2 500–2 600	30	8	38	71	33	1·0	0·011	0·011
2 600–2 700	30	10	40	70	30	0·98	0·01	0·0098
2 700–2 800	30	11	41	69	28	0·97	0·09	0·0087
2 800–2 900	30	12·5	42·5	67	24·5	0·96	0·08	0·0077
2 900–3 000	30	13·5	43·5	66	22·5	0·95	0·07	0·0067
3 000–3 100	30	14·5	44·5	65·5	21·0	0·94	0·06	0·0056
3 100–3 200	30	15·5	45·5	65	19·5	0·92	0·05	0·0046
3 200–3 300	30	17	47	64	17	0·9	0·04	0·0036
3 300–3 400	30	18·5	48·5	63	14·5	0·85	0·04	0·0034

$\Sigma p\Delta b = 0{\cdot}5885$

Ideal sound articulation = 90 per cent.

C.B. No. 1. Microphone.

1 000–1 100	30	38·2	68·2	88	19·8	0·93	0·032	0·0297
1 100–1 200	30	32·6	62·6	88	25·4	0·97	0·029	0·0281
1 200–1 300	30	18·5	48·5	88	39·5	1·0	0·027	0·027
1 300–1 400	30	16	46	87·5	41·5	1·0	0·025	0·025
1 400–1 500	30	1·5	31·5	87	55·5	1·0	0·022	0·022
1 500–1 600	30	2·5	32·5	86	53·5	1·0	0·021	0·021
1 600–1 700	30	5·5	35·5	85	49·5	1·0	0·019	0·019
1 700–1 800	30	7·5	37·5	84	46·5	1·0	0·018	0·018
1 800–1 900	30	10	40	82	42	1·0	0·017	0·017
1 900–2 000	30	16	46	80	34	1·0	0·016	0·016
2 000–2 100	30	10	40	78	38	1·0	0·015	0·015
2 100–2 200	30	9	39	76	37	1·0	0·014	0·014
2 200–2 300	30	14	44	75	31	0·98	0·013	0·0127
2 300–2 400	30	19	49	74	25	0·96	0·012	0·0115
2 400–2 500	30	38·2	68·2	73	4·8	0·68	0·012	0·0082
2 500–2 600	30	32·6	62·6	71	8·4	0·77	0·011	0·0085
2 600–2 700	30	38·2	68·2	70	1·8	0·6	0·01	0·006

$\Sigma p\Delta b = 0{\cdot}2987$

Ideal sound articulation = 63 per cent.

Discussion at a Joint Meeting of the Meter and Instrument Section and the Wireless Section, 8th April, 1932.

Col. A. S. Angwin: I am particularly interested in the volume indicator, which first came to be used in telephony through the application of radio telephony to the international telephone network. It enables the technical operator to ensure that the outgoing speech from the central terminal station fully loads the radio transmitter. The instrument used in Great Britain for this purpose has not been standardized by the C.C.I., although it is used in the European standard equipment at Paris. The C.C.I. have, however, specified that it must register the integrated volume of the input terminal speech in a minimum time of 220 milliseconds. It is equally important to specify the time of restoration, which depends upon the characteristics of the electrical circuit and the mechanical features of the recording instrument. The development of this instrument, which will ultimately take the form of an international standard, demands active co-operation between the instrument maker and the user.

Captain B. S. Cohen: In 1907 the late Mr. G. M. B. Shepherd and I read a paper* before the Institution on the subject of telephone transmission measurements, and it is instructive to compare the measuring apparatus of that period with what we have available to-day. As sources of alternating current we had such things as microphone hummers, small alternators, and vibrating wires, and to produce a frequency of more than 1 200 cycles per sec. was quite an achievement. Wave-form was studied with an early Duddell oscillograph (our instrument was, I believe, the second oscillograph made), and other measurements were made by means of thermo-galvanometers and barretters. Acoustic measurements were practically impossible, and it is true to say that the thermionic valve has enabled us to make quantitative electro-acoustic measurements. Very little literature dealing with acoustics existed; on the one hand there was Lord Rayleigh's treatise, which was rather above the heads of the communication engineers of the day, and on the other hand there were the elementary text-books on sound, light, and heat, drawn up for the use of examination candidates and generally valueless for any other purpose. All that has now been changed; the development of the principles of electro-acoustics enables us to make calculations based on the same type of formulæ as those we are accustomed to use in electrical work. Electrical engineers have been primarily responsible for the developments in electro-acoustics, and I therefore consider that the tendency to employ acoustical analogues of electrical units is to be encouraged. For example, we should measure acoustic capacitances and acoustic resistances in acoustic microfarads and acoustic ohms. The line-transmission side of the telephone system has been brought to such a pitch of perfection that nowadays even in the longest telephone communications a full 50 per cent of the volume losses and 75 per cent of the articulation losses occur in the telephone instruments. In order to improve these instruments it is therefore important to take advantage of all possible developments in electro-acoustical methods. It is stated in the paper (page 606) that the thermophone method is recommended by the C.C.I.; it would, I think, be more correct to say that it had been adopted by that body. The C.C.I. did not recommend it, but they agreed that any method of calibration might be used provided it gave satisfactory results. The British Post Office uses W. West's adaptation of the Rayleigh-disc method, and the German Post Office uses the compensation method. Both give very similar results to those given by the thermophone method. I should like to refer to an important point in connection with the frequency characteristics of loud-speakers and telephone apparatus, on which there is some misconception. The frequency-response characteristic of a loud-speaker can be measured under a number of different conditions, as, for example, (*a*) in free space or in a sound-absorbing chamber designed to be the equivalent of free space, (*b*) in a room which reverberates but in which a warble frequency oscillating a few cycles to each side of the particular frequency at which we are making the measurement, is applied to the instrument; and (*c*) in a reverberant room, the apparatus being moved about during the test. The three methods do not necessarily all give the same results. Practical tests show that one cannot make accurate measurements of the characteristics of acoustic instruments except under the conditions existing in a completely sound-absorbing room, or—what is equivalent to that—in free space. With reference to the author's statement regarding side-tone (page 623), it should be pointed out that the effect on the efficiency of conversation when no side-tone exists, due to the raising of the voice of the speaker, is a secondary matter compared with the improvement which occurs at the receiving end when the side-tone is considerably reduced. The improvement is particularly noticeable with a room-noise level of the order of 55 decibels, which is about the figure that obtains in a rather noisy city office where typewriters are being used and traffic is passing in the street outside. Telephonic conversation in certain cases under such circumstances is very difficult without a side-tone reduction device.

Mr. P. G. A. H. Voigt: I should like to describe a convenient device for measuring the amount of modulation with which we have to deal. The circuit, shown in Fig. A, is a development of one* devised some years ago for giving an automatic grid-bias voltage proportional to the peak voltage of the incoming signal. It makes use of the principle employed in high-frequency rectification. When a signal arrives which tends to make the grid-potential positive, the resultant grid current charges the condenser C negatively. If the leak is removed or disconnected, the voltage of the negative charge on the condenser becomes equal to the peak voltage of the incoming signal, and when the signal stops, the charge gradually

* B. S. Cohen and G. M. Shepherd: "Telephonic Transmission Measurements," *Journal I.E.E.*, 1907, vol. 39, p. 503.

* Patent No. 222981.

leaks back at a rate depending upon the capacitance of the condenser and the resistance of the various leakage paths. The calibration of an arrangement of this sort is very easy, as it can be done by means of direct current (e.g. from a grid battery) with an accuracy sufficient for most purposes. When no signal is being received, the maximum current will pass through the meter, and this

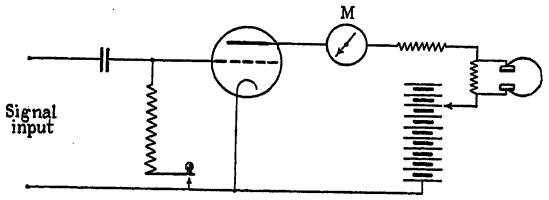


FIG. A.

NOTE.—The milliammeter M may be mounted upside down so that zero peak volts (max. current) is on the left.

can be adjusted to a convenient amount by varying the anode resistance and/or h.t. voltage. When a signal arrives, the condenser is charged negatively, and the mean anode-current diminishes. The amount of the decrease is almost exactly proportional to the peak signal voltage, providing that bottom-bend rectification is not occurring. (Bottom-bend rectification occurs during very loud

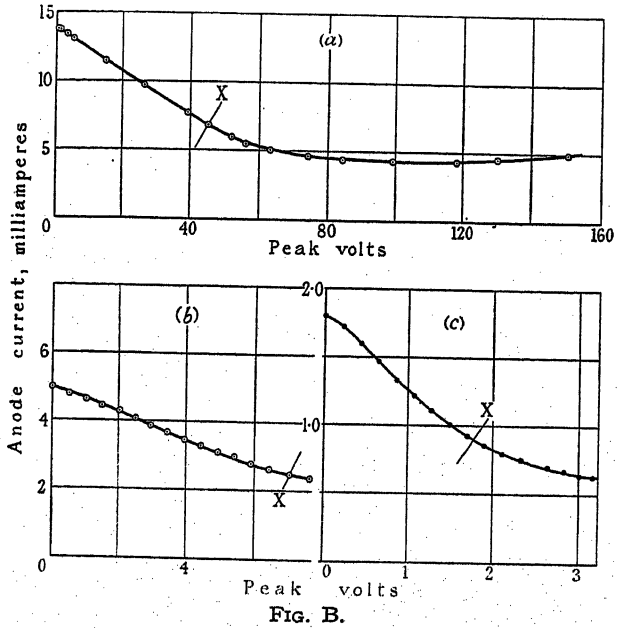


FIG. B.

(a) L.S.5 valve, 25 000-ohm resistance, 500 volts H.T.
(b) P.M.252 valve, 13 000-ohm resistance, 100 volts H.T.
(c) P.M.1 H.F. valve, no resistance, 100 volts H.T.
X marks the "half no-signal-current" position below which bottom-bend rectification occurs with sustained tones.

sustained tones when the mean anode current has been depressed to less than half the "no signal" current. Below this point the d.c. calibration becomes invalid for such tones.) Fig. B shows the calibration curves of three such "modulation indicators" for different valves and working conditions. I shall next refer to a microphone I have developed, which has very nearly a straight-line characteristic. Although some of the condenser microphones which have been calibrated by thermophone methods seem to have straight-line characteristics, measurements in free air show that owing to the obstacle effect and the cavity effect the characteristics have very much more "top" than is generally supposed. The microphone I have devised is so small that it presents

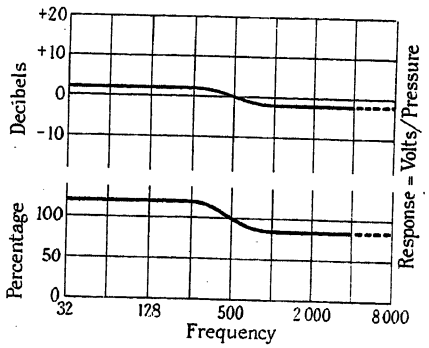


FIG. C.

practically no obstacle to the sound waves, and, moreover, as it is slightly oval it has no cavities. The characteristic is not quite straight because the elastic forces controlling the diaphragm are provided by an air

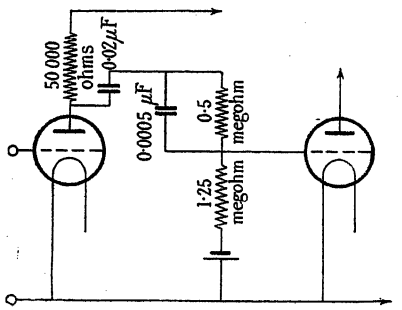


FIG. D.

cushion, which expands and contracts isothermally at low frequencies and adiabatically at high frequencies, causing a slight change (3 decibels) in response. Fig. C shows the free-air response of this microphone plotted on

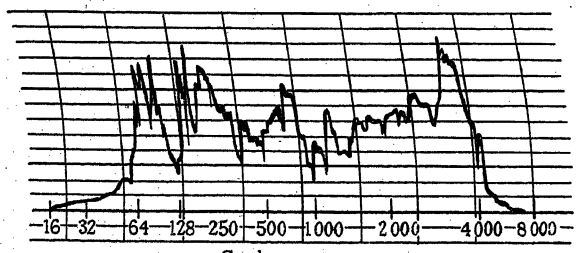


FIG. E.

a decibel and also on a percentage basis. Fig. D shows a simple correction circuit to compensate for this error. I shall now demonstrate a method of recording on automatic apparatus the characteristic curve of a loudspeaker under working conditions. The tone source consists of a constant-amplitude heterodyne frequency record which starts at 8 000 and goes down the scale to 16 cycles per sec., the note being switched off momen-

tarily each octave. The pick-up, which is of a special type, has a uniform response on this record from 4 000 down to 50 cycles per sec. A microphone of the type I have described picks up the sounds from the loud-speaker, and the currents are amplified and fed to a modulation indicator such as that shown in Fig. A. The current is about 14 milliamperes when there is no signal. As the signal comes in, the current drops in proportion to its peak value, and is recorded by an Everett-Edgcumbe graphic ammeter (0–30 mA) on a piece of paper. A loud-speaker can thus be calibrated in $1\frac{3}{4}$ minutes, a permanent record of the characteristic (see Fig. E) being obtained.

Dr. L. E. C. Hughes: The paper would be improved by the consistent adoption of logarithmic frequency and power-level scales, with the decibel unit for the latter. The question of amplitude distortion, which is serious in some types of carbon transmitters, is not considered in the paper. Has the author any evidence to show how far amplitude distortion, with the consequent introduction of alien frequencies, affects the articulation as calculated by Collard's method? Curves similar to those given in Fig. 13 for loud-speakers can, of course, be obtained for transmitters and microphones used for high-quality circuits. The directive properties of microphones and loud-speakers are, I think, better exhibited by polar response-curves for particular frequencies than by curves of frequency response in various directions. Such polar curves show the contribution of the microphone or loud-speaker to what I propose to call "reverberation distortion." As I speak, listeners in various locations receive different ratios of the direct sound intensity radiated, which depends on the polar distribution of my voice and falls off with the square of the distance, and the reverberant sound intensity, which depends only on the total sound-power radiated and the acoustic properties of the surroundings and is approximately constant throughout the auditorium. (Prominent reflections are omitted for the sake of simplicity.) The impression of the received sound depends on this ratio; moreover, the ears are directional for the directly-radiated sound and not for the reverberant sound. The response of a microphone for a directly-radiated sound is the polar response in the direction of arrival of that sound; its response for the reverberant sound, in so far as the latter may be idealized into a multitude of waves arriving from all directions with heterogeneous phases, is the mean-spherical response. We can distinguish two components in a sound, the directly-radiated component of wave-form determined by the source, and the reverberant component, which consists of all the partials mixed up, modified by the absorptions of the surroundings, and intermingled to some extent with all the sounds in a slightly antecedent interval of time. The reverberant component carries with it tone-colour and atmosphere, but, if excessive, it blurs the definition of the directly-radiated wave. If the response of a microphone in a particular direction is greater than its mean-spherical response, the ratio of the direct to the reverberant intensity in the electrical output of the microphone is increased above that at the location of the microphone; if less, diminished. Likewise, on reproduction, the polar response of the loud-speaker determines the directly-radiated intensity, and the mean-spherical response the reverberant intensity. The ratio between these intensities is altered by any difference between these responses. The polar response-curves of microphones and loud-speakers are therefore drawn to show the concentration, i.e. the ratio of polar response to mean-spherical response, in decibels, which is the measure of alteration of direct to reverberant intensity in the converted sound. Fig. F shows such curves for microphones. The axis is towards the left and only half of the curve is shown, in view of symmetry. The three lower curves apply to the normal condenser-transmitter, which exhibits considerable variation with azimuth and frequency, but the concentration is substantially zero below 1 000 hertz.* The 1 000- and 5 000-hertz curves apply to a condenser microphone with a parabolic mirror, which is used searchlight fashion for broadcasting operas. The greatly increased axial concentration, giving definition to the contributions of individual artistes, necessitated the mixing-in of reverberant sound from another microphone.† The

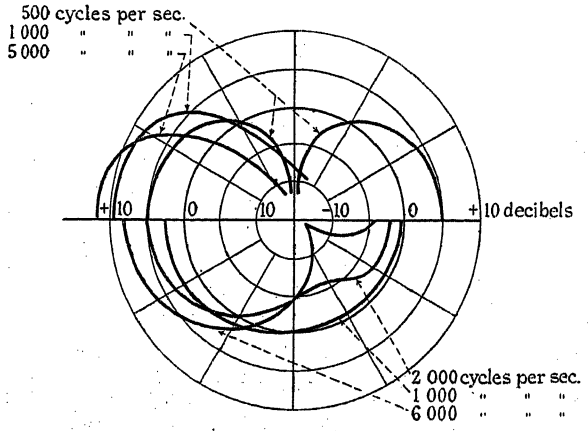


FIG. F.

500-hertz curve applies to the Olson ribbon-microphone, which was specially developed for use in sound-film work. The response concentration curve is practically the same at all frequencies, and thus the quality of the direct sound picked up does not change with azimuth; the ratio of the direct to the reverberant intensity is changed over a wide range by rotating the microphone.‡ J. P. Maxfield§ has derived empirically a technique for placing the microphone in relation to the artiste, the acoustic properties of the set, the camera, and the focal length of camera lens, so as to obtain a consistent illusion of single-channel sound-perspective. This technique depends essentially on reverberation distortion. If telephone transmitters could be provided with greater directivity, it would result in a greater discrimination against room noise, which consists mainly of reverberant sound.

Mr. W. West: It would appear from the sound-field charts shown in Fig. 5 that errors up to about 40 per cent are liable to occur in the measurement of loud-

* See L. J. SIVIAN: *Bell System Technical Journal*, 1931, vol. 10, p. 107.
† See O. B. HANSON: *Journal of the Acoustical Society of America*, 1931, vol. 3, p. 90.
‡ See H. F. OLSON: *ibid.*, 1931, vol. 3, p. 67.
§ *Ibid.*, 1931, vol. 3, p. 69.

speaker characteristics in this type of acoustic chamber. While I do not mistrust the experimental accuracy of the tests on which the charts are based, I am in doubt as to their interpretation. The tests were made with a fixed microphone, near one end of the chamber, and a movable source of sound, consisting of the open end of a length of conduit tubing. The tubing penetrated through a small aperture at the other end of the chamber, and the position of the open end was adjusted from outside. Any reflected sound would therefore not only arrive at the microphone with a different phase from the direct sound, but it would also react on the source of sound to alter the rate of emission of energy. Careful study of loud-speaker characteristics taken in this chamber has yielded no evidence of errors as large as 40 per cent, attributable to reflections. On the other hand, experiments with a loud-speaker at distances up to 5 ft. from the microphone have been made with a tone of 500 cycles per sec., both steady and warbling, through a range of about $\frac{1}{4}$ octave. The results obtained were identical within experimental errors of the order of 1 per cent. Turning to the subject of microphone calibration, a reference to the recent paper by Stuart Ballantine would, I suggest, form a useful addition to the Bibliography.*

Dr. G. W. Sutton: We are rapidly approaching a turning point in the matter of the relative importance of voice-ear and mechanical methods of testing telephone instruments. Until quite recent times the former was relied upon almost exclusively—even for such measurements as that of the efficiency of transformers. Now, however, the use of voice-ear methods tends to be restricted to a certain class of standardization work, and its technique is being more stringently regulated in the light of our increasing knowledge of the complex nature of the sense of hearing. Mechanical devices are taking the place of the voice, and amplifier-voltmeters that of the ear, in much of the routine testing and research work which was formerly dependent upon voice-ear methods. It has hitherto been implicitly assumed that results obtained by the new methods should be in exact numerical agreement with those obtained by the old, and that failure to achieve such agreement is a measure of the weakness of the new methods. I believe that this outlook on the problem will only be associated with the transition stage, and that we shall emerge from it as further experience is accumulated. The remark on page 614 that "the only measurements which, at present, give definite quantitative results are obtained from voice-ear tests" is a mis-statement of the present position, particularly if the time taken by the tests and the number of operators required are regarded as important factors. The principal drawback to voice-ear methods is the extreme indefiniteness of individual test results, owing to the large part played by the subjective factor. I suggest that a frequency-characteristic test, combined with a mechanical-efficiency test, will provide more quantitative information as to the performance of, say, a carbon microphone than anything but an extensive and elaborate set of voice-ear volume and articulation tests. With regard to Fig. 6, are the ordinates in terms of volts across the loud-speaker, or on the grid of the output valve? Is the curve in terms of the "free-air" or the "diaphragm-pressure" calibration of the condenser microphone? This has an important bearing on the results shown in Fig. 7, with which our own experimental observations are somewhat in conflict. We are in closer agreement with the results obtained by the Post Office Research Station.* In this connection the ingenious method of obtaining a sound field of uniform intensity over a wide frequency range which is described by Grützmacher and Just† is worthy of note. We have used a somewhat simpler development of their method. It would be interesting to know why in Fig. 11 the author gives the output of a Bell receiver in terms of voltage. Surely this is a current-operated device. The method of side-tone measurement illustrated in Fig. 57 appears to me to be unnecessarily complicated. In some side-tone measurements recently carried out for us in the S.F.E.R.T. laboratory, a method which we suggested was employed very successfully. In principle it consists of reducing by a known amount (10, 20, or 30 decibels) the side-tone level of an instrument connected to some representative line, and then determining the "side-tone-reference-equivalent" by direct comparison with the high-quality circuit. The reduction of level is obtained by inserting a small (10-ohm) continuously-variable non-inductive resistance in series with the local receiver. Across this resistance a potential-dividing resistance of 1 000 ohms is connected, and this is provided with tapping points at full volume, 10 decibels less than full volume, 20 decibels less, and so on. The potential so obtained is applied to the grid of a 2-stage amplifier, in the output circuit of which a second receiver is connected. The 10-ohm variable resistance is so adjusted that the levels in the first and second receivers are equal when the voltage tapping is set at full volume. This may be done either by voice-ear balance or by mechanical means, using an artificial ear. The level in the second receiver may then be reduced by known amounts by altering the tapping point. With regard to the neon-lamp oscillator for producing the rhythmic howl used in mechanical testing (page 625), I have heard this apparatus in operation and am much impressed with its simplicity. Such oscillators are usually of rather an uncertain wave-form and frequency, however, and there may be the risk of attaining simplicity at the expense of exact reproducibility and reliability. These two, together with speed, are the chief advantages of mechanical testers. I am greatly interested to see that the existing voltage test for carbon-microphone "fry" is likely to give place to a noise-measuring scheme. We have always found the voltage test somewhat unsatisfactory for routine work, and it would seem that some method similar to that employed for measuring "background noise" in high-quality carbon microphones would be preferable. I note on page 624 the strange term "pads" of artificial line. Does this term really meet a long-felt want?

Mr. L. C. Pocock: Curve 1 of Fig. 3 is rather misleading if it is taken to apply to practical conditions. Both Curve 1 and the thermophone characteristic (broken curve) are taken under simplified conditions,

* This has since been included.

* *Post Office Electrical Engineers' Journal*, 1929, vol. 22, p. 193.
† *Elektrische Nachrichten-Technik*, 1931, vol. 8, p. 104.

because reverberation and directional effects are eliminated. I have in the last few days compared a condenser microphone under typical conditions in a moderately-damped room with a new type of moving-coil microphone* which has a substantially flat characteristic from low frequencies up to about 10 000 cycles per sec. The condenser-microphone characteristic obtained in this comparison does not rise to such a high peak as is shown by the free-air or plane-wave method of measurement. As regards Fig. 16, does not the greater sensitivity of the hand-set microphone as compared with the solid-back transmitter annul a great deal of the advantage of the anti-side-tone circuit, owing to the large interference effect of the room noise? We really require two microphone characteristics, one at speech level and the other at a necessarily lower noise-level. The curve of Fig. 16 is apparently advanced by the the author as a good feature, but if the sensitivity to noise is equally great the general increase in sensitivity is not without disadvantages. It is universally realized that sound volume alone is not enough, that good articulation is of great importance, and that to this must be added an appreciation of the value of reducing side-tone. I have compared three modern telephone sets—A, B, and C—of substantially equal loudness and efficiency. A has less side-tone than B, and the ratio of their intelligibilities ($A : B$) turns out to be 4 : 3; A has the same amount of side-tone repression as C, but superior articulation; the ratio of their intelligibilities ($A : C$) is 4 : 2·5. These measurements were made over a line equivalent to the limiting line permitted by the C.C.I., with the addition of room noise and line noise. It is therefore evident that both side-tone and articulation have a considerable effect upon intelligibility. As indicated in the paper, side-tone reacts upon the speaker and affects the initial-speech loudness; the same is true of received speech. A subscriber tends to speak loudly if he hears a faint voice from the far end and to speak quietly if he hears a loud voice. If a man on a short local line is talking to a man on a long local line, the man on the long line gets very little microphone current and consequently his sound intensity as received is rather low. The man on the short local line receives a large current, on the other hand, and his speech comes through loudly. Thus the man on the long local line hears a loud voice and speaks quietly, and the man on the short local line hears a faint voice and shouts. The natural effect of unequalized local lines is therefore an undesirable one, reacting upon the subscribers to cause an intensification of the difference in transmission in the two directions, and it seems likely that it will be found advantageous to equalize approximately the local-line transmitting losses.

Dr. G. F. Dutton: The design, testing, and specification of transmitters and receivers has lagged behind that of other apparatus. The operating conditions of circuit apparatus and cables have received considerable attention, and their specification and testing are carried out to a high degree of accuracy. The terminal apparatus—the transmitter and the receiver—was until quite ecently not treated in a scientific manner. Even now, vhen reliable methods of obtaining the frequency-esponse characteristics are available, the latter do not enter into the commercial specification of instruments. Sufficient data are now available from the combined work of British and American telephone engineers to determine the optimum frequency transmission band, which is controlled by several factors. First there is the articulation efficiency, which requires a frequency range of 500 to 4 000 cycles per sec., for 95 per cent articulation efficiency. The high-frequency range is limited by the transmission-line characteristics, but in any case there is very little gain in going above 4 000 cycles per sec. The lower frequency cut-off is desirable in order to protect the transmitter from amplitude overload, which reduces the articulation efficiency by modulating the upper frequencies and introducing spurious noise-frequency components. The lower frequency cut-off must, of course, take place in the mechanical acoustical system of the transmitter. The transmitter auto-transformer circuit acts as a low cut-off filter, the

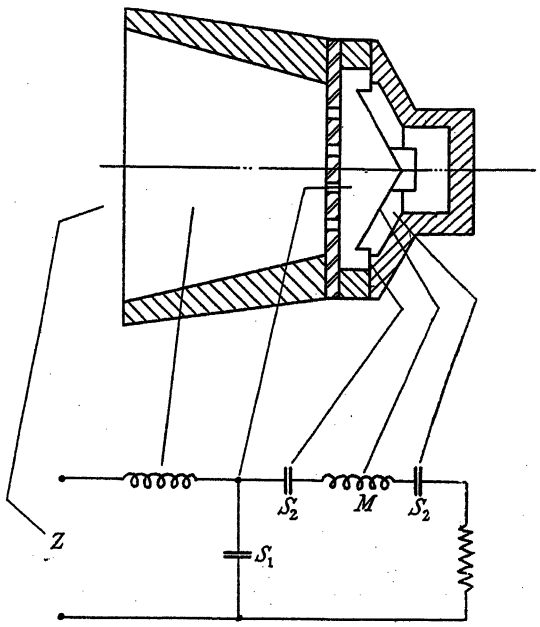


FIG. G.

cut-off being in the region of 200 cycles per sec. Fig. G gives the electrical circuit of the mechanical system of the Neophone transmitter. It will be seen that the system is a mechanical band-pass filter, and by the suitable choice of diaphragm mass and air-chamber stiffness the upper and lower cut-off frequencies can be made at about 500 and 4 000 cycles per sec. In order that the upper cut-off may be sufficiently high, the mass M of the diaphragm must be small and the air-chamber compliance S_2 must be great. A known variation of efficiency within the frequency range of a transmitter will give a known variation in articulation. From this property a frequency-response envelope can be specified, and all transmitters must fall within this envelope. The application of this idea would obviate the laborious articulation and volume-counting tests. From a manufacturing point of view, this method of testing would allow the production staff to keep a check on the quality, and any variation in the response characteristics could

* See *Bell System Technical Journal*, 1931, vol. 10, p. 565.

be traced to errors in assembly or the constants of materials. In Figs. 7 and 11 the transmitter-response peak and the receiver fundamental resonance just fail to coincide; if the peaks are allowed to coincide a considerable reduction in articulation results. It would be a great advantage if the receiver resonance could be reduced in sharpness, as the characteristics of the transmitter and receiver could then merge with greater safety. In order to flatten the receiver characteristic without increasing vibrational resistance, it would be necessary to reduce the mass of the diaphragm. This can only be done if the diaphragm is stretched, since with its present thickness of about 0·01 in. it acts as a plate and requires only clamping to maintain rigidity. If the thickness of the diaphragm is reduced to one-half or less, the air-gap must either be increased, with consequent loss of efficiency, or the diaphragm must be given a radial stretch.

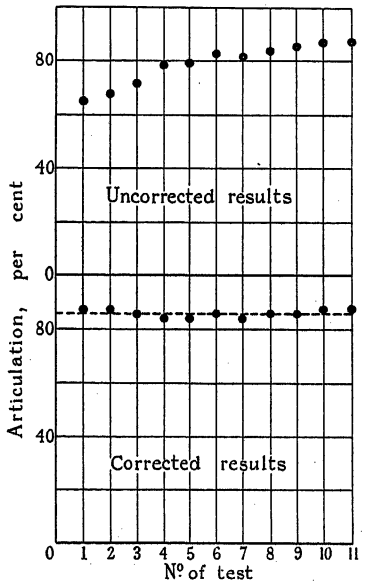


FIG. H.

This stretching would result in a more uniform product, since the air-gap would be uniform and not influenced by the slight buckling which often occurs in a thick diaphragm. An improvement in the transmitter can only be obtained by considering the overall characteristics of the system. I should like to know whether the author has found any difference between the articulation efficiencies obtained when using male and female listeners. Whereas a man usually holds the receiver close to the ear, women rarely place the receiver so as to cover the ear completely; either the hat or the hair prevents a close contact. Under these conditions the receiver cap forms an open shell which will resonate and pick up room noise, thus interfering with the received signals. Regarding the measurement of transmitter "frying," the chief difficulty lies in the erratic character of this effect. Some types of granules "fry" with a continuous "mush" sound, whereas other types splutter and crackle between intervals of comparative quiet. Carbon mush, or "background noise" as it is generally called, is always present even when the current density is very low; the current density at which the mush breaks into a definite "fry" is critical, and I regard it as the best determining factor.

Dr. J. Collard: In his remarks on articulation testing (page 621) the author mentions that the effect of the training of the crew is very large, and although he describes two methods for overcoming it he gives no practical results to illustrate the application of these methods. Fig. H gives the results of some of my own articulation tests. A series of 11 tests were carried out by the same crew on the same circuit at different times, and the tests occupied a period of about 2 weeks. The articulation values actually obtained are shown in the top half of the diagram. At the beginning of the series the crew were unfamiliar with the technique, and were getting the low value of 65 per cent. As time went on they became more familiar with the technique, and the value gradually rose, until, towards the end of the period, values of about 87 per cent were recorded. This very big variation shows that to take actual articulation results without any form of correction is very dangerous. While these tests were being made the crew was calibrated from time to time on a standard circuit very similar to that described by the author, and from the results the crew factor was deduced in accordance with my method (mentioned on page 622). This factor enables the effect of training to be removed from ths given set of observations. The results of the 11 tests having been corrected in this way, the series of values given in the lower half of Fig. H were obtained. It will be seen that these corrected points group themselves very well about the average value shown by the dotted line, and show no signs of the training effect which is so prominent in the original values. This diagram therefore illustrates two important points; first, that it is extremely necessary to apply some form of correction to articulation results in order to remove the training effect, and secondly, that the method used here does really succeed in eliminating this effect.

Mr. D. A. Oliver: I think that the author's typical results, especially the frequency-response curves, might with advantage have been supplemented by rather more qualification. For instance, whereas a condenser-microphone response-curve is usually very stable, the corresponding curve for a carbon transmitter (e.g. Fig. 7) is often difficult to reproduce. Sometimes the second peak in the curve will appear during repeated measurements, and sometimes it will not; this may have some influence on articulation in connection with speech-transmission tests. The first peak, being due to mechanical resonance, is very stable for many types of carbon transmitters. The author's way of quoting results in volts per dyne per cm^2 is possibly a little misleading, because, on account of the severe non-linearity of the carbon transmitter, for high pressures that value falls and for very low pressures it becomes quite large. I suggest that, for a routine commercial test at any rate, it is desirable to quote the output for a stated constant sound-testing pressure, so as to eliminate or reduce the severe effect of non-linearity. I should also like to emphasize the desirability of plotting loud-speaker response curves in decibels. As regards the method (page 625) of testing carbon microphones by

holding them in front of the guard of the loud-speaker, I believe that the two standard pressures adopted are 30 and 20 dynes per cm^2 for the two guard positions. It is not uncommon to find in some commercial moving-coil loud-speakers, over a frequency band of 400 to 1 800 cycles per sec., extreme response variations of well over 6 decibels; and as the difference in level between 20 and 30 dynes per cm^2 is only about 3·5 decibels, some more uniform source of sound pressure seems to be desirable. I have been experimenting successfully with a cylindrical chamber of 5 cm diameter, having a small moving-coil piston drive at one end when the mouth of the microphone is held over a hole in a plate closing the other end of the chamber. With this device it is possible to set up a fairly uniform pressure in the chamber—and hence on the transmitter diaphragm—over the desired frequency range. The limitation, of course, is that the size of the chamber must be small compared with the wavelength.

Mr. F. D. Smith: My experience of absolute measurements of sound intensity has been limited for the most part to water as the medium of propagation. Although there is no difference in the fundamental principles determining the transmission, propagation, and reception of sound in the two media, the enormous numerical disparity between their acoustic resistances necessitates a somewhat different technique. This difference appears in the methods adopted to establish measurements on an absolute basis. The Rayleigh disc and the condenser microphone, which are so valuable in air, are practically useless in water; on the other hand, various devices which are of value in water are relatively useless in air, with the exception of the moving-coil instrument. In water the latter should preferably be used as an inertia instrument,* i.e. with a small heavy rigid piston carrying the moving coil and so designed that the stiffness and damping terms in the equation of motion are negligible compared with the inertia term. I should be interested to know whether the instrument in this particular form has been used in air. As regards sound measurements by means of a Rayleigh disc in a resonating tube, it has recently been found† that a condition of eddies and turbulent motion is set up in such a tube when the sound intensity exceeds a certain value. Does this occur at the intensity normally used in connection with the Rayleigh disc? While it is difficult to avoid excess of detail in a comprehensive summary of so wide a scope as that covered by the paper, I think the use of pattern numbers without sufficient technical explanation, e.g. "C.B. No. 1," should be avoided.

Mr. E. J. Barnes (*communicated*): With reference to the calibration of condenser microphones, the author points out the difference between the curves obtained in terms of the "pressure on diaphragm" and the "pressure in free air," but does not particularly emphasize the different uses to which the two calibrations may be put. The former is what is required when calibrating, say, the artificial ear. The latter calibration is required when ıe microphone is to be used for broadcasting and nilar purposes. In this case, however, the curves shown by the author are for sound arriving from a direction normal to the diaphragm. In many other cases, e.g. when reflected sound may also reach the microphone, sound may arrive from any direction, and it is necessary to consider the "polar" characteristics of the microphone. The author also points out that the calibration of the microphone when spoken into from very short distances probably falls between the two calibrations. Under these conditions the exact calibration is probably indeterminate on account of interaction between the microphone and the source. I should like to call attention to the ease and simplicity of calibrations made by means of the Rayleigh disc. The discs are not difficult to make, handle, or calibrate, and the whole apparatus is not expensive. The author omits to mention the electrostatic-force method of microphone calibration, using a grille in front of the diaphragm. I think it should be pointed out that the frequency characteristics of carbon microphones shown in the paper are for plane waves falling on the mouthpiece, and that they do not quite represent the condition of actual use. Some form of artificial mouth is required to obtain data corresponding to "use" conditions. In this connection I should like to say that the mechanical methods of testing commercial telephones described by the author are by no means final. An "artificial ear" incorporating a moving-coil unit is now under trial to replace the method described, for testing receivers. It is interesting to recall that in 1916 when the warble tone produced by a rotating interrupter, described on page 625, was first used, although quite good results on transmitter tests could be obtained, attempts to make an artificial ear for receiver testing completely failed. In those days we had no condenser microphones and only rough methods of obtaining the characteristics of transmitters and receivers, although valve amplifiers and rectifiers for measuring telephone currents were in use. Many thousands of special microphones required for war purposes were tested by these mechanical means. On page 626 the author gives a figure for the maximum permissible voltage due to transmitter "fry": actually it is specified that the power dissipated in the resistance replacing the receiver shall not exceed 0·00015 microwatt.

Mr. G. A. V. Sowter (*communicated*): The curves shown in Fig. 13 emphasize how difficult it is to judge the performance of a loud-speaker from pressure measurements made on the axis, owing to the fact that the output falls away rapidly as the angle with the axis increases. Bridge measurements of effective resistance and inductance in air and *in vacuo* provide a useful guide to performance, since the sound output can be calculated from them, and Dr. McLachlan and I have made a large number of experiments in this direction. Unfortunately we had no suitable vacuum chamber, and the readings therefore included diaphragm loss, but even curves of apparent radiation resistance are a better guide to probable performance than axial pressure curves. A general analysis of loud-speaker action can be made from our results* in conjunction with a recent paper by Dr. McLachlan.† These show that the large peaks in

1. SMITH: "The Absolute Measurement of Sound Intensity," *Proceedings ysical Society of London*, 1929, vol. 41, p. 487.
DA C. ANDRADE: "Sound, Sand, and Smoke: New Light on Old ," *Proceedings of the Royal Institution*, 1931, vol. 26, p. 568.

* *Philosophical Magazine*, 1931, vol. 12, p. 771.
† *Proceedings of the Physical Society of London*, 1932 vol. 44 ,p. 408.

the middle of the frequency scale of Fig. 13 are due to the cone executing symmetrical modes, which, in a homogeneous system, are characterized by nodal circles. The lower resonances are due in part to air-column vibrations. I think the author might add to the Bibliography references to acoustic measurements by Dr. McLachlan and myself on the natural oscillations of various types of loud-speakers,* and to Dr. McLachlan's recent paper mentioned above. The general analysis made in the latter is of great utility to designers.

Mr. H. R. Harbottle (*in reply*): Col. Angwin draws attention to the C.C.I. Specification for an instrument by which speech volume is to be measured. This states that the instrument shall read within 2 decibels of its final deflection 0·2 sec. after suddenly switching on a sinusoidal alternating current, and restore 2 sec. after the current ceases. The American volume indicator only fulfils the first of these requirements. The speech meter of the British Post Office under the first condition has the characteristics specified, and its reading with speech is therefore much more definite. However, the volume indicator has received the recommendation of the C.C.I., inasmuch as it has been adopted by that body for use on the S.F.E.R.T.

Comparison of the present paper with the one cited by Captain Cohen confirms his view that the rapid progress in acoustical engineering during the past 15 years has been largely due to the thermionic valve. The determination of the performance of acoustical and mechanical systems by their analogy to electrical networks is greatly simplified by the use of a similar system of units. The C.C.I. did not particularly recommend the thermophone method of calibrating condenser microphones and high-quality moving-coil receivers, but this method has been adopted for use on the S.F.E.R.T. Although the various methods of calibration give approximately the same result, it is considered that one method, and that the one which represents practical conditions as closely as possible, should be used as a standard of reference. The fact that the various methods of loud-speaker calibration do not necessarily give the same results emphasizes the necessity of having some such acoustic room as that described in the paper, for obtaining the performance of the loud-speaker *per se*. The relative importance of the two effects of side-tone on transmission efficiency depends entirely on the location of the instrument, although the reduction in articulation due to local room noise is perhaps the more general.

The calibration of the peak voltmeter described by Mr. Voigt would be rather uncertain unless some definite leak, low in comparison with the normal grid-filament leakage paths, were used. The performance curve of the condenser microphone (Fig. C) has been substantially confirmed in the Research Section of the British Post Office, the sensitivity being approximately 0·3 millivolt per dyne per cm^2, when polarized by 300 volts. It would appear that the source of alternating current for operating the loud-speaker is far more uncertain than that of the simple heterodyne oscillator, in which there is no mechanical wear.

* *Wireless World*, 1929, vol. 24, pp. 346 and 886; also *Philosophical Magazine*, 1931, vol. 11, p. 1; and 1932, vol. 13, p. 115.

In reply to Dr. Hughes, the particular type of scale to be adopted for plotting frequency characteristics depends on the manner in which these are to be used. The shape of the characteristic obtained by any particular method will depend to a large extent on the scale of units adopted. The effect of amplitude distortion on the results obtained by Dr. Collard's method of measurement of articulation efficiency has not up to the present been investigated at any length, although its presence will modify the results to some extent. In confirmation of this, it was found that the articulation efficiency obtained by a British crew on the S.F.E.R.T., having the sending and receiving ends distorted to represent the frequency characteristics of a carbon microphone and commercial receiver respectively, was 59 per cent, although the same crew obtained an articulation efficiency of 54 per cent when an actual microphone and receiver were substituted. The polar curves given by Dr. Hughes in Fig. F make a useful supplement to the information collected in the paper on the performance of condenser microphones.

Mr. West draws attention to the surprisingly large discrepancies in the curves of Fig. 5. Since there is perfect similarity between loud-speaker characteristics taken in the acoustic room with warble and steady tones, it would appear that the errors shown in Fig. 5 are too great. This may be due to the following factors. (*a*) Interaction between the source and the measuring microphone. (*b*) Conduction along the tube. (*c*) If any reflections were present, these would react on the source. (*d*) Any small errors in measurement would be amplified at large distances, since the output from the measuring microphone is multiplied by the distance.

Replying to Dr. Sutton, mechanical devices for replacing the voice and ear in transmission testing are still in their infancy, and no method is yet available which can be universally used. Voice-ear testing is naturally a tedious and expensive method of measuring the performance of telephone instruments, especially from a manufacturer's point of view. Although mechanical devices have been obtained which give agreement with speech on particular instruments, yet the turning point, when voice-ear testing will be restricted to purely standardization work, has by no means been reached. With regard to Fig. 6, the ordinates are in terms of dynes per cm^2 per volt across the loud-speaker. The curve has not been corrected for the free-air calibration of the condenser microphone used. Dr. Sutton draws attention to a method of obtaining a uniform sound field. A modification of this method which has been tried in the Research Section of the British Post Office is not altogether satisfactory in the acoustic room, on account of the polar distribution of the output from the loud-speaker and interaction between the control microphone and the loud-speaker. This microphone must be placed near the flare loud-speaker horn if sufficient control is to be obtained. The following method is being tried instead. The flare of the exponential horn will terminate in a small wooden box 3 ft. 6 in. × 3 ft. 6 in. × 2 ft. 6 in. axially. This box will be lined to a depth of 18 in. with gamgee tissue backed by celotex. The gamgee tissue will be continued for about 18 in. into the flare of the horn itself. The horn will

thus terminate in a cylindrical space surrounded by gamgee tissue. The pressure on the axis of the horn will be measured by a modification of the artificial ear. A small-bore tube, open at one end, is made acoustically long by drawing in strands of darning wool of varying lengths from the other end. The pressure existing at the open end will be measured by means of a condenser microphone which communicates with the tube at a distance of about 18 in. from this end. The output of the Bell receiver was quoted in terms of voltage for purposes of comparison with Fig. 10. Since the corresponding impedance curves are given in Fig. 12, the current curves can easily be plotted. The side-tone reference-equivalent mentioned by Dr. Sutton can be obtained by the method of side-tone measurement given in the paper. It would not appear to be more complicated than the method used by him in Paris, since, when testing any new type of instrument, the reference equivalents of its sending and receiving efficiencies must be obtained—and the side-tone test requires only one additional measurement. This method of reducing the sound in the receiver subjected to side-tone is perhaps a little cumbersome, but this can be simplified by only using one receiver fitted with a modified artificial ear. In this, acoustic attenuation occurs in a small-bore tube containing threads of darning wool which leads from the cavity in the artificial ear to a hole in a standard earcap. The frequency of a neon-tube oscillator is given by the equation*

$$f = \frac{1}{KR \log_e \left[(E - E_e)/(E - E_s)\right]}$$

where E_s, E_e, and E, are the striking, extinguishing, and applied voltages respectively. Since the two former are inherently variable, it would be expected that the performance of neon-tube oscillators would be rather uncertain. However, this method of producing the rhythmic howl used in mechanical testing of instruments is still in the experimental stage, and particular attention is being directed to its stability.

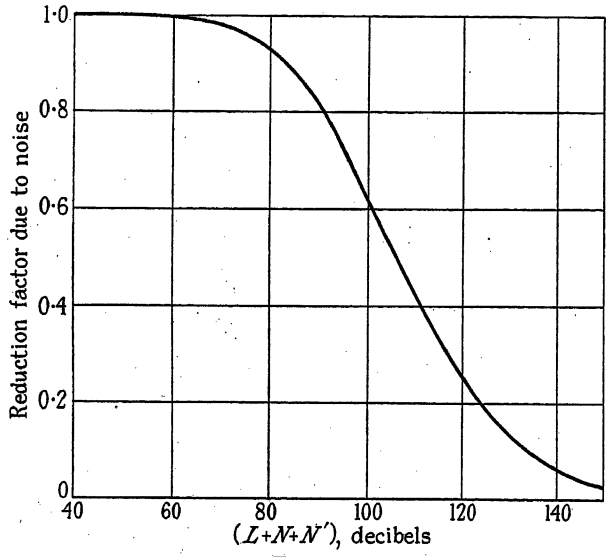


FIG. J.

L (>15<50 decibels) = volume efficiency of circuit in terms of standard C.B. subs. circuit with 300-ohm local line.
N (>40<80 decibels) = room noise level (decibels) above normal threshold of hearing at 1 000 cycles per sec.
N' = addition to effect of room noise due to side-tone.

Curve 1 of Fig. 3 is for sound waves incident at right angles to the diaphragm of the condenser microphone, and it is interesting to note that when directional effects are taken into account Mr. Pocock's experiments substantially confirm this, although the peak which they give does not appear to be so high as that obtained by the free-air method. This, of course, may be due to his assuming an incorrect characteristic for the moving-coil microphone. As regards Fig. 16, the curves are intended to show only the relative effects of distance on the efficiencies of the two types of microphones; they do not necessarily give absolute values. When considering the effect of room noise on the two types it should be remembered that the side-tone on the new hand micro-telephone instrument incorporating an anti-side-tone transformer is of the order of 10 decibels less than on the standard solid-back instrument, and, although the reduction in efficiency with distance is not so great with the former as with the latter, yet the masking due to room noise will still be less. The reduction in the articulation efficiency of a particular circuit due to room noise will depend on three factors. (*a*) The attenuation of the circuit. (*b*) The level of the local room noise (N decibels) heard in the free ear. (*c*) The amount of room noise (N' decibels) heard in the receiver due to the side-tone of the instrument. The amount of reduction due to these causes is clearly demonstrated in Figs. J and K. Fig. J was obtained for the working circuit of the British Post Office with a junction (L decibels) varying from 15 to 50 decibels, and for a range in room noise equivalent to a tone of 1 000 cyles per sec. from 40 to 80 decibels above the threshold value. If the relative side-tone for a particular instrument is known with a certain room noise N decibels, N' can be obtained from the appropriate curve in Fig. K. Then, when this instrument is used under these conditions on a circuit having an attenuation equivalent to L, the reduction factor in articulation corresponding to $L + N + N'$ is obtained from Fig. J. If Mr. Pocock's ideal of equal local-line losses were secured, many

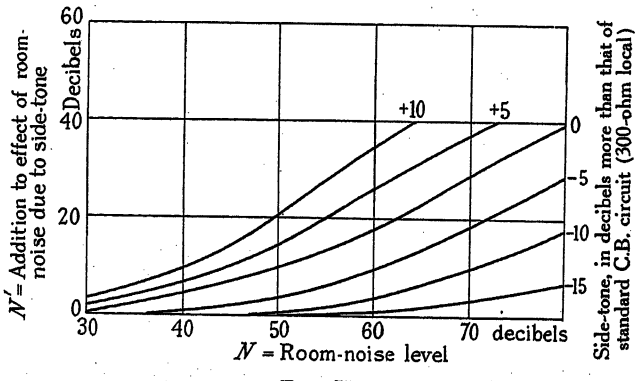


FIG. K.

* L. E. RYALL: "The Correlation of the A.C. and D.C. Striking Voltages of a Neon Lamp," *Journal of Scientific Instruments*, 1930, vol. 7, p. 177.

problems of the telephone engineer would be greatly simplified.

No great differences in the articulation efficiencies obtained by male or female crews have been recorded, but the possible cause of discrepancy mentioned by Dr. Dutton was not present in the tests, since the receiver was pressed to the ear in both cases, the hair, etc., causing no interference.

Unfortunately no results of articulation tests for investigating either method of crew calibration mentioned in the paper, made in the Research Section of the British Post Office, are available at present. However, the curve in Fig. L is of similar shape to the upper curve in Dr. Collard's Fig. H, and similarly illustrates the practice effect. This curve gives the results of a series of tests made in Paris by an expert articulation crew during 1930. The circuit used was the S.F.E.R.T., incorporating a low-pass filter which had a nominal cut-off of 1 500 cycles per sec. The band articulation of the circuit was 0·65, which, from Fig. 34, corresponds to an ideal sound articulation of 93 per cent or an ideal syllable articulation of 82 per cent, since logatoms of the consonant-vowel-consonant combination were used in the tests.

In reply to Mr. Smith, owing to the comparatively low intensities used in the tube method of adapting the Rayleigh disc for acoustic measurements no evidence of eddies being produced has been observed. Any eddies which are produced will occur at the walls and will penetrate only a very small distance into the tube.

Mr. Barnes states that the specification for the maximum permissible amount of "fry" is given in terms of power. The voltage measurement given in the paper has been found to correspond to this power.

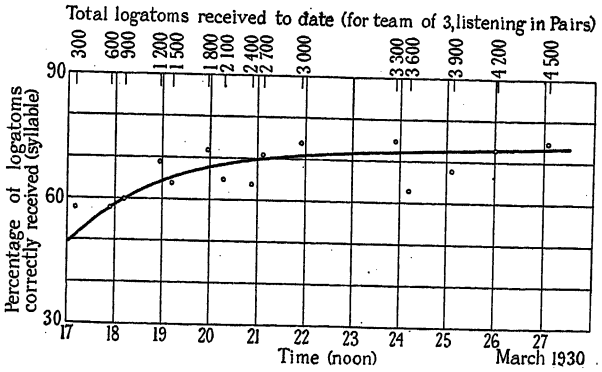


FIG. L.—Articulation-practice effect. British team—Paris, 1930.

The additions to the Bibliography suggested by the various speakers have been made and will considerably add to its value for reference purposes.

WIRELESS STUDIES OF THE IONOSPHERE.*

By Professor E. V. Appleton, M.A., D.Sc., F.R.S.

(*Lecture delivered before the* Wireless Section, *25th May*, 1932.)

(1) Introductory and Historical.

The first indication that the upper atmosphere played an important role in wireless transmission was Marconi's successful communication between England and America in 1901. The late Lord Rayleigh† was the first to realize that some other factor than that of wave diffraction was involved in this case, and the mathematical investigations of Poincaré,‡ Nicholson,§ Macdonald,‖ and Watson,¶ amply confirmed this view. These mathematical studies of the diffractive bending of electromagnetic waves round a conducting, or partially conducting, sphere showed conclusively that the signal intensity should decrease with increase of distance much more rapidly than was actually found to be the case in practice. Some factor favouring wireless transmission had evidently not been taken into account.

Fortunately, suggestions as to the nature of this factor were already to hand, for, in 1902, Kennelly** and Heaviside†† had independently pointed out that if the upper atmosphere were electrically conducting there would be a tendency for the wireless waves to be guided round the protuberance of the earth's surface, energy being conserved between two concentric shells and not lost to space. As was clearly pointed out by Kennelly, the acceptance of the hypothesis of the existence of an upper-atmospheric conducting layer meant that "the voluminal wave energy would, beyond a certain radius from the emitting station, diminish in simple proportion to the distance, neglecting absorption losses at the upper and lower reflecting surfaces, so that at twice the distance the energy per square metre of wave front would be halved."

Later quantitative studies of long-distance long-wave propagation, of which the most complete is that by Round, Eckersley, Tremellen, and Lunnon,‡‡ have afforded very strong indirect evidence for the existence of the atmospheric conducting region postulated by Kennelly and Heaviside, in that substantial agreement has been obtained between the observed values of received signal intensity and those predicted from Watson's theory§§ of the propagation of waves round a conducting sphere which is itself surrounded by a concentric reflecting shell.

The most direct evidence of the existence of an upper conducting layer has, however, been derived from experiments on short-distance transmissions in which the question of the earth's curvature is not involved. Such experiments, besides yielding a direct proof of the existence of the Kennelly-Heaviside layer, also gave the first indications of its height above the earth's surface. Their further prosecution has added considerably to our knowledge of the electrical structure of the upper atmosphere. Most of the advantages of short-distance experiments can be traced to the fact that there is, in such cases, a ground wave arriving at the receiving station which, when used as a kind of reference standard, enables us to study the amplitude, phase, and polarization of waves reaching the receiver via the upper atmosphere.

(2) The Direct Proof of the Existence of the Kennelly-Heaviside Layer.

In 1925, Barnett and I* gave an experimental proof of the existence of an atmospheric ionized layer and also a determination of its height. The proof of the existence of the layer was in two parts. The first part of the experiment consisted in causing a small continuous change of the emitted frequency to take place at the sending station, the resultant alteration of the signal at the receiving station being noted. It was found that the gradual alteration of the emitted frequency produced regular maxima and minima of received signal intensity, such as might be expected from interference between ground waves and downcoming waves from the upper atmosphere. The first part of the experiment therefore proved the existence of two sets of waves arriving at the receiving station. In the second part of the experiment the signal variations were compared (*a*) on a vertical aerial and (*b*) on a loop the plane of which coincided with the plane of propagation. From this comparison the angle of incidence of the variable set of waves at the ground was shown to be less than $\frac{1}{2}\pi$. In a series of experiments carried out at Cambridge on signals from London, 88 km away, the angle of incidence was found to be 20°, indicating that the variable waves which caused the interference system with the constant ground waves came down from the upper atmosphere. Each part of the experiment provided, moreover, an independent estimate of the height of the reflecting region. This was found to be of the order of 90 km for the range of wavelengths used (300 to 400 m).

The experimental proof of the existence of the Kennelly-Heaviside layer given by Barnett and myself was immediately followed by confirmatory independent experiments of a very exhaustive nature carried out by Smith-Rose and Barfield,† who also found equivalent heights of the order of 100 km for a similar range of wavelengths.

* This is a convenient term, suggested by Mr. R. A. Watson Watt, connoting the ionized regions of the upper atmosphere.
† See Bibliography, (1). ‡ *Ibid.*, (2). § *Ibid.*, (3).
‖ *Ibid.*, (4). ¶ *Ibid.*, (5). ** *Ibid.*, (6).
†† *Ibid.*, (7). ‡‡ *Ibid.*, (8). §§ *Ibid.*, (9).

* See Bibliography, (10). † *Ibid.*, (11).

(3) Methods of Measuring the Equivalent Height of the Atmospheric Reflecting Layer.

Since 1925, various direct wireless methods have been proposed for measuring the "effective" height in the atmosphere at which the waves are reflected, and most of the information we possess concerning the electrical structure of the upper atmosphere has resulted from their application. It is found that these methods can be divided into two classes, (*a*) those in which the angle of incidence of the downcoming waves is measured, and (*b*) those in which the group-time for a signal to travel from sender to receiver via the upper atmosphere is measured. Because of the greater use that has been made of them we shall consider only the methods of class (*b*) in detail here.

To measure the time required for a signal to travel to the upper atmosphere and back, we require to impress on the waves emitted by the sending station some distinguishing feature by means of which we can recognize them on their subsequent arrival at the receiving station. Now an electric wave possesses two characteristics, namely, frequency and amplitude, so we are at liberty to modulate either of these quantities. Both frequency-modulation and amplitude-modulation have, in fact, been used and we now proceed to consider the two methods in greater detail.

(*a*) *Frequency-change method.*

To illustrate the principles of this method, which was first used by Barnett and myself, let us consider a sending station at S (Fig. 1), the signals from which are received at a station R. Two sets of waves reach the receiving station, namely, the ground waves along SR and the atmospheric waves along SABCR. Let the optical path of the atmospheric waves be P and the path-difference between the atmospheric and ground paths be D. Although SR is independent of the frequency, both P and D are functions of that quantity. If n is the difference in the numbers of wavelengths in the atmospheric and ground paths we have

$$n = \frac{D}{\lambda} = f\frac{D}{c} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f is the frequency of the waves, and λ and c are respectively the wavelength and velocity of the waves in free space. Since, however, D is equal to $(P - \mathrm{SR})$, (1) becomes

$$n = f\frac{(P - \mathrm{SR})}{c} \quad . \quad . \quad . \quad . \quad (2)$$

Now in the application of the frequency-change method we measure the alteration of n for a known alteration of f, the quantity $\Delta n/\Delta f$ being experimentally determined. From (2) we have

$$c\Delta n/\Delta f = (P - \mathrm{SR}) + f dP/df \quad . \quad . \quad . \quad (3)$$

or

$$(c\Delta n/\Delta f + \mathrm{SR}) = P + f dP/df \quad . \quad . \quad (4)$$

The quantities on the left-hand side of (4) are those determined in the experiment, and we see that only when the upper atmosphere is non-dispersive (i.e. $dP/df = 0$) can we determine the optical path P in this way. I have, however, shown* that, since the optical path is equal to $\int \mu ds$ for the atmospheric wave track (μ being the refractive index along an element of track length ds), we have

$$P + f\frac{dP}{df} = P' = c\int\frac{ds}{U} \quad . \quad . \quad . \quad . \quad (5)$$

U being the group velocity of the waves at any point. P' is termed the equivalent path of the atmospheric waves. From (4) and (5) we have, therefore,

$$\left(\mathrm{SR} + c\frac{\Delta n}{\Delta f}\right) = P' = c\int\frac{ds}{U} \quad . \quad . \quad (6)$$

from which we see that the essential quantity measured in the frequency-change method is the group-time for a signal to travel along the atmospheric track SABCR.

(*b*) *Amplitude-change method.*

This method was first proposed and used by Breit and Tuve,† who used a station emitting short pulses of

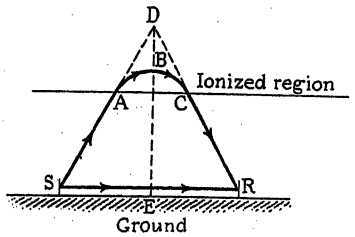


Fig. 1.

radio-frequency energy and measured directly the time interval, t, between the arrival of the pulses received via the ground and via the atmosphere. Evidently for such a case we have, using the nomenclature of (*a*) and Fig. 1 above,

$$t = \frac{P' - \mathrm{SR}}{c} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

or

$$(\mathrm{SR} + ct) = P' = c\int(ds/U) \quad . \quad . \quad . \quad (8)$$

A comparison of (6) and (8) shows that the same quantity, namely, the equivalent path of the atmospheric waves, is measured in both the frequency-change and the amplitude-change methods. Since U is, in general, less than c, the equivalent path P' is greater than the actual path s of the atmospheric waves, so that the equivalent height (calculated by simple triangulation from the equivalent path) is greater than the actual maximum height reached by the atmospheric waves. By far the greater part of the measurements of equivalent heights has been made with the distance SR less than 20 km, so that the angle of incidence of the atmospheric waves on the ionized region has usually been very small.

(4) Results of Equivalent-Height Measurements.

As I have already stated, the results of the first measurements of the equivalent height of the Kennelly-Heaviside layer, made with 400-m waves, indicated an equivalent height of 90–100 km. Further continuous

* See Bibliography, (12). † *Ibid.*, (13).

series of measurements showed that, for most nights after sunset, the height increases slightly, reaching its maximum value about half an hour before sunrise, after which, by a somewhat rapid change, the height is reduced to the lower day-time value. During a normal night the equivalent height may increase to 120 km; but, on certain occasions, during the hours just before dawn, 400-m waves penetrate the Kennelly-Heaviside layer (region E) and are reflected at an upper stratum which is richer in ionization. On such occasions equivalent heights of 230 to 350 km have been measured. With the advent of sunrise the ionization in region E is restored and deviation at a height of 100 km again takes place.

When shorter wavelengths are used, the number of hours in the day when region E is penetrable is greater. This is illustrated in Fig. 2, in which the equivalent path of the atmospheric waves (which, in this case, is approximately twice the equivalent height) is exhibited

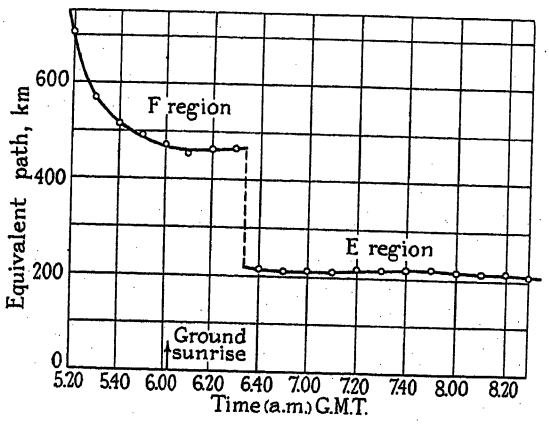


FIG. 2.—Teddington transmission received at King's College, 21st March, 1930.

as a function of local time. A wavelength of 150 m was used here and it is seen that the discontinuous jump from region F to region E occurred after ground sunrise.

Further experiments carried out with a wide range of wavelengths have shown that the following general statements can be made concerning the relation between equivalent height and wave frequency for observations with waves incident normally on the ionized regions. Low-frequency waves are reflected at region E, the equivalent height increasing slightly with increase of frequency. At a certain small critical range of frequencies, reflection at region E ceases and reflection at region F begins, and there is a discontinuity in the range of values of equivalent heights. With further increase of frequency the equivalent height of region F increases rapidly, so that for very high frequencies of the order of 10^7 cycles per sec. the waves penetrate region F at normal incidence and pass out into space. The mean critical penetration frequency for region E varies diurnally and seasonally; it is a maximum at local noon, and a minimum just before dawn. It is also greater at summer noon than at winter noon. The penetration frequency for region F is a maximum two or three hours after local noon, and its diurnal and seasonal variations are not so marked as is the case with the penetration frequency for region E.

The above considerations are of considerable use in correlating the different results obtained by investigators who have used the group-retardation method. The first observations of this kind, made by Breit and Tuve in 1926, with 70-m waves, yielded values of the equivalent height ranging almost continuously from 88 km to 212 km. Further day-time measurements made by Breit, Tuve and Dahl* appeared, however, to fall into two series, of mean values 110 km and 220 km. These results I have interpreted† as confirming my theory of the existence of two reflecting regions. Kenrick and Jen,‡ working with 67-m waves, found, in a 24-hour run, values ranging from 240 km in the day-time to 370 km just before dawn. According to the explanation given above, the waves used by these observers were penetrating the Kennelly-Heaviside layer (region E) and were reaching region F. In 1930, Gilliland,§ using 74-m waves, came to the conclusion that day-time reflection was obtained from two layers of equivalent heights 119 km and 235 km.

In Germany, Goubau and Zenneck,‖ using 530-m waves, found that all their results could be explained in terms of single and multiple reflection from one layer, the equivalent height of which was of the order of 94 km. The waves used by these investigators were clearly of such a length that penetration of region E did not take place either by day or by night.

In 1931 Schafer and Goodall,¶ using 97-m and 187-m waves, concluded that their data indicated the existence of two distinct ionized regions or layers, while more recently Builder and I,** also using the group retardation method, have found that the echoes from region F are often split into doublets which we consider may be the two magneto-ionic components into which the single pulse is resolved by magneto-ionic dispersion. Still more recently, Rukop and Wolf,†† using a method for the continuous recording of equivalent heights of reflection, have also observed the same doubling of echoes from region F, which they also are inclined to attribute to the influence of the earth's magnetic field.

Summarizing the above discussion we may say that from experiments carried out at vertical incidence there is now considerable evidence for the existence of two reflecting regions, namely the Kennelly-Heaviside layer (region E) and an upper region which is normally more intensely ionized (region F). The equivalent height of region E is found to increase slightly with increase of frequency, the average value being of the order of 100 km. At any hour of the day there is a certain small critical range of frequencies for region E, and frequencies higher than this reach region F. For frequencies slightly higher than the critical range the equivalent height is of the order of 230 km. At first the equivalent height of region F may decrease slightly with increase of frequency, but for still higher frequencies there is a marked increase of equivalent height with increase of frequency. Very high frequencies penetrate both regions E and F.

* See Bibliography, (14). † *Ibid.*, (15). ‡ *Ibid.*, (16).
§ *Ibid.*, (17). ‖ *Ibid.*, (18). ¶ *Ibid.*, (19). ** *Ibid.*, (20).
†† *Ibid.*, (21).

(5) The Nature of Downcoming Waves.

The applications of the frequency-change method, supplemented by the use of different types of antenna installations, has permitted the determination of the characteristics of downcoming waves and of the nature of the causes of nocturnal signal variations and directional wireless errors. Ratcliffe and I,* using 400-m waves, have carried out experiments to determine the polarization of waves reflected by the upper atmosphere. These experiments showed that, in south to north transmission over a distance of about 80 miles in England, the polarization is approximately circular with a left-handed sense of rotation.† In attempting to explain this result we pointed out that the influence of the earth's magnetic field might well be expected to give this result, but that the most direct test of such an interpretation "would be to carry out similar experiments at corresponding points in the Southern Hemisphere, where the resulting polarization should be right-handed if the effect is due to the action of the earth's magnetic field." More recently A. L. Green, working under the Australian Radio Research Board, has been able to test this point and has found that, under comparable conditions, downcoming waves in Australia are approximately circularly polarized with a right-handed sense of rotation.

Experiments on the polarization of downcoming waves are of more than scientific consequence. The British Radio Research Board, on its formation in 1920, instituted a fundamental inquiry into the cause (and, if possible, the elimination) of night errors in direction-finding. It was recognized at that time that such errors were caused by the arrival at the point of observation of waves which were abnormally polarized, but the origin of such abnormal polarization was unknown. As a result of Green's experiments it can now be regarded as certain that the influence of the earth's magnetic field is such as to produce this polarization. We can say that nocturnal errors in wireless direction-finding are due to the arrival at the receiver of waves which leave the emitter as plane-polarized waves in a direction inclined to the horizontal and reach the ionosphere. There, under the influence of the earth's magnetic field, they are separated into two elliptically polarized waves which undergo differential absorption and refraction. On reaching the receiver they cause fading and errors in the observed direction of the emitting station.

In connection with the nature of the changes which take place in the characteristics of downcoming waves at night, we have to contemplate the possibility of changes in (*a*) the angle of incidence, (*b*) the intensity, (*c*) the phase, and (*d*) the polarization of the downcoming waves. By studying fading on different types of antenna reception systems, Ratcliffe and I have concluded that intensity variations and, to a lesser degree, phase variations are the chief causes of signal fading. For the conditions of our experiments (400-m waves and distance of propagation 131 km) we concluded that variations in the angle of incidence and in the rotation of the plane of polarization are not responsible in any marked degree for signal fading.

Although the cause of signal variations has been traced mainly to resultant intensity fluctuations of the downcoming waves, it is important to note that such intensity fluctuations are most probably themselves the result of an interference mechanism. The intensity fluctuations are found to exhibit a kind of periodicity which varies with the wavelength and with the distance of transmission. If T is the period of the fluctuations and λ the wavelength, T/λ is found (within certain limits) to be an increasing monotonic function of the distance of transmission. It is highly probable that interference between the various magneto-ionic components of singly- and multiply-reflected downcoming waves is partly responsible for resultant intensity fading, for variations in the ionic concentration along the tracks of the waves will cause differential alterations of the optical paths and thus an alteration in the phase differences between the various components which arrive at a receiving station. According to this view, the influence of the earth's magnetic field is important in causing signal fading as well as directional errors. Another probable type of interference mechanism is the simultaneous reflection of waves from different portions of a layer of non-uniform stratification, the irregularities of which alter with time.

The reflection coefficient ρ (defined as the ratio of the emergent to the incident amplitude) can be determined when doubly-reflected waves are observable, as is often the case with the group-retardation method. We allow for the fact that the doubly-reflected wave has made a double journey to the layer and back so that in the case of vertical incidence ρ is equal to twice the ratio of the intensities of the second- and first-order components. The value of ρ at night can approach unity, values of 0·3 to 0·7 being quite common for 70-m waves.

(6) The Magneto-ionic Theory of Electric Wave Propagation.

The foundations for any theoretical discussion of the action of the ionosphere in wave propagation are to be found in the theories of Eccles* and Larmor.† Eccles showed that the action of free ions is to increase the phase-velocity of the waves in the medium so that the refractive index is diminished below unity. Larmor emphasized the importance of considering electrons as the effective electrical carriers, and pointed out that for any substantial diminution of the refractive index below unity to be attained without large absorption, as is required to account for the experimental data, we must consider the frequency of the electron collisions with the gas molecules as being small compared with the frequency of the wireless waves.

For negligible friction the theories of both Eccles and Larmor lead to the following expression for the refractive index:—

$$\mu^2 = 1 - \frac{4\pi N e^2}{mp^2} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where N is the number of electric charges (of charge e and mass m) per cm^3, and p is the angular frequency of

* See Bibliography, (22).
† The observer is here supposed to be looking along the direction of wave propagation.

* See Bibliography, (23). † *Ibid.*, (24).

the waves. As shown by Lorentz* and, with greater relevancy to our particular problem, by Hartree† this equation, when corrected to take account of local polarization effects and interelectronic influences, becomes

$$\mu^2 = 1 - \frac{4\pi Ne^2}{mp^2 + \frac{1}{3}(4\pi Ne^2)} \quad . \quad . \quad . \quad (10)$$

In both cases it is seen that the presence of electrical carriers causes a reduction of the refractive index below unity.

Let us now consider the case of the refraction of waves by a medium of gradually varying refractive index, the variation being so gradual that the medium may be considered as homogeneous throughout a few wavelengths.‡ Let ABCDEF be a ray which enters the ionized medium at B and emerges from it at E (see Fig. 3). Let θ_i be the angle of incidence at the lower boundary of the ionized region and μ_0 the refractive

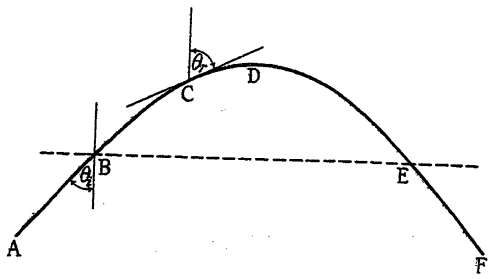


FIG. 3.

index of unionized air. Then it is easily shown that the refractive index at any point C is given by the relation

$$\mu_0 \sin \theta_i = \mu \sin \theta_r \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where θ_r is the angle between the ray direction at C and the vertical. Now at the highest point of the trajectory we have $\theta_r = \frac{1}{2}\pi$ and, since μ_0 may be considered equal to unity,

$$\mu_D = \sin \theta_i \quad . \quad . \quad . \quad . \quad . \quad (12)$$

From (10) and (12) it is easy to show that

$$N_D = \frac{3mp^2 \cos^2 \theta_i}{4\pi e^2(3 - \cos^2 \theta_i)} \quad . \quad . \quad . \quad (13)$$

so that, if θ_i and p are known, the ionization at the highest point of the trajectory may be estimated. The corresponding formula, neglecting the polarization term, is

$$N_D = \frac{mp^2 \cos^2 \theta_i}{4\pi e^2} \quad . \quad . \quad . \quad . \quad (14)$$

In 1925 I pointed out,§ (and it was also independently shown by Nichols and Schelleng),‖ that the ionic refraction theories of Eccles and Larmor were incomplete, in that no account had been taken of the influence of the earth's magnetic field. Such influence is of great importance if, as seems most probable, the effective electrical carriers in the upper atmosphere are chiefly of electronic mass. Expressions for the refractive index of an ionized medium for transmission along and at right angles to an imposed magnetic field were immediately derivable from the dispersion theory of Lorentz. The significance of such expressions in connection with the interpretation of wireless wave phenomena was discussed by Barnett and myself,* and also by Nichols and Schelleng. These discussions showed that the influence of the earth's magnetic field is quite marked for all wavelengths except those which can be classed as ultra-short.

In general, however, we are concerned not only with propagation along and at right angles to the earth's magnetic field, but with propagation in any direction relative to the field. Given the nature of the medium and the direction of propagation, we wish to know the refractive index, absorption coefficient, and polarization, for the two component waves which travel. Formulæ

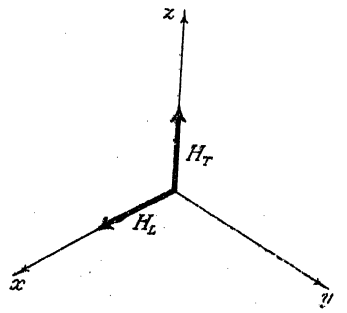


FIG. 4.

for cases in which friction is neglected have already been discussed, but in view of the importance of the differential absorption of the two components a more general treatment is desirable. An extension of the dispersion theory given by Lorentz to the general case of any direction of propagation is therefore given below.

Let us consider a case of propagation of plane waves along the axis of x (see Fig. 4), it being assumed that the imposed magnetic field has components along x and z (longitudinal and transverse respectively) but not along y. Let E, H, P, and j, be respectively the electric force, magnetic force, polarization, and convection-current density, at any point.

The field equations of Maxwell may be written, in Lorentz units,

$$\left.\begin{aligned} \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} &= \frac{1}{c}\left(\frac{\partial E_x}{\partial t} + j_x\right) \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= \frac{1}{c}\left(\frac{\partial E_y}{\partial t} + j_y\right) \\ \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} &= \frac{1}{c}\left(\frac{\partial E_z}{\partial t} + j_z\right) \end{aligned}\right\} \quad . \quad . \quad (15)$$

and

$$\left.\begin{aligned} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} &= -\frac{1}{c} \cdot \frac{\partial H_x}{\partial t} \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -\frac{1}{c} \cdot \frac{\partial H_y}{\partial t} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\frac{1}{c} \cdot \frac{\partial H_z}{\partial t} \end{aligned}\right\} \quad . \quad . \quad . \quad (16)$$

* See Bibliography, (25). † *Ibid.*, (26).
‡ The wavelength within the medium is here indicated.
§ See Bibliography, (27). ‖ *Ibid.*, (28).

* See Bibliography, (29).

Since plane wave propagation takes place along the x axis we have

$$\frac{\partial}{\partial y} = \frac{\partial}{\partial z} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

so that the six equations in (15) and (16) become, in order,

$$\frac{\partial E_x}{\partial t} + j_x = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$-\frac{\partial H_z}{\partial x} = \frac{1}{c}\left(\frac{\partial E_y}{\partial t} + j_y\right) \quad . \quad . \quad . \quad . \quad (19)$$

$$\frac{\partial H_y}{\partial x} = \frac{1}{c}\left(\frac{\partial E_z}{\partial t} + j_z\right) \quad . \quad . \quad . \quad . \quad (20)$$

$$\frac{\partial H_x}{\partial t} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$-\frac{\partial E_z}{\partial x} = -\frac{1}{c}\cdot\frac{\partial H_y}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$\frac{\partial E_y}{\partial x} = -\frac{1}{c}\cdot\frac{\partial H_z}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

These equations immediately tell us certain facts about the type of propagation. From (18), since

$$j_x = \frac{\partial P_x}{\partial t} \quad . \quad . \quad . \quad . \quad (24)$$

we have

$$E_x + P_x = 0 \quad . \quad . \quad . \quad . \quad (25)$$

This means that since the electron current vibrations will, in general, have a forward component at right angles to the wave-front, there will also be a longitudinal component of electric force, so that the waves are not wholly transverse. Equation (21) implies that there is no corresponding forward component of the magnetic vector, so that it is convenient to specify the polarization of the wave in terms of H_y and H_z.

From (19), (20), (22), and (23), we derive the four wave-equations

$$\left.\begin{aligned}
\left(\frac{1}{c^2}\cdot\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)E_y + \frac{1}{c^2}\cdot\frac{\partial}{\partial t}(j_y) &= 0\\
\left(\frac{1}{c^2}\cdot\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)E_z + \frac{1}{c^2}\cdot\frac{\partial}{\partial t}(j_z) &= 0\\
\left(\frac{1}{c^2}\cdot\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)H_z - \frac{1}{c}\cdot\frac{\partial}{\partial x}(j_y) &= 0\\
\left(\frac{1}{c^2}\cdot\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)H_y + \frac{1}{c}\cdot\frac{\partial}{\partial x}(j_z) &= 0
\end{aligned}\right\} \quad . \quad (26)$$

Following Lorentz, let us assume that all the field vectors are represented by expressions containing the factor $e^{ip(t-qx)}$.* We then have

$$\left.\begin{aligned}
\frac{\partial}{\partial t} &= ip & \frac{\partial^2}{\partial t^2} &= -p^2\\
\frac{\partial}{\partial x} &= -ipq & \frac{\partial^2}{\partial x^2} &= -p^2q^2
\end{aligned}\right\} \quad . \quad (27)$$

* i is here written for $\sqrt{(-1)}$.

Using (27), our four wave-equations (26) become

$$\left.\begin{aligned}
(c^2q^2 - 1)E_y - P_y &= 0\\
(c^2q^2 - 1)E_z - P_z &= 0\\
(c^2q^2 - 1)H_z - cqP_y &= 0\\
(c^2q^2 - 1)H_y + cqP_z &= 0
\end{aligned}\right\} \quad . \quad . \quad . \quad (28)$$

from which we deduce that

$$\frac{E_y}{E_z} = \frac{P_y}{P_z} \quad \text{and} \quad \frac{H_y}{H_z} = -\frac{E_z}{E_y} \quad . \quad . \quad . \quad (29)$$

and thus $(EH) = 0$. The resultant components of E and H in the wave-front are thus at right angles to each other.

To obtain the values of the complex refractive index (cq) we must find the relations between the components of electric force and polarization in terms of the imposed magnetic field and the ionization of the medium. We assume that the imposed magnetic field has longitudinal and transverse components H_L and H_T respectively and that the medium contains N electrons (each of charge e and mass m) per cm^3. We further assume that each electron makes on the average ν collisions per second with the air molecules.

Extending the treatment given by Lorentz* and allowing for the fact that the electrons possess negative charges we find

$$E_x = (\alpha + i\beta)P_x + i\gamma_T P_y \quad . \quad . \quad . \quad . \quad (30)$$

$$E_y = (\alpha + i\beta)P_y - i\gamma_T P_x + i\gamma_L P_z \quad . \quad (31)$$

$$E_z = (\alpha + i\beta)P_z - i\gamma_L P_y \quad . \quad . \quad . \quad . \quad (32)$$

where

$$\alpha = -\frac{mp^2}{4\pi Ne^2} - \frac{1}{3}; \quad \beta = \frac{mp\nu}{4\pi Ne^2}; \quad \gamma_L = \frac{mp[H_L e/(mc)]}{4\pi Ne^2}$$

and $\gamma_T = \dfrac{mp[H_T e/(mc)]}{4\pi Ne^2}$. To facilitate practical calculations the values of e and H_T (and H_L) are here written in electrostatic units and gauss respectively.

From (25) and (30) we have

$$P_x = \frac{-i\gamma_T P_y}{1 + \alpha + i\beta} \quad . \quad . \quad . \quad . \quad (33)$$

Substituting in (31) we therefore obtain

$$E_y = (\alpha + i\beta)P_y - \frac{\gamma_T^2}{1 + \alpha + i\beta}P_y + i\gamma_L P_z \quad (34)$$

while

$$E_z = (\alpha + i\beta)P_z - i\gamma_L P_y \quad . \quad . \quad . \quad (32)$$

Using (34) and (32) now and eliminating E_y, E_z, P_y, and P_z, we have

$$\gamma_L^2 = \left\{(\alpha + i\beta) - \frac{1}{c^2q^2 - 1}\right\} \times \left\{(\alpha + i\beta) - \frac{\gamma_T^2}{1 + \alpha + i\beta} - \frac{1}{c^2q^2 - 1}\right\}$$

* Lorentz considers positive electrical carriers.

from which we find

$$c^2q^2=1 + \frac{2}{2(\alpha+i\beta)-\frac{\gamma_T^2}{1+\alpha+i\beta}\pm\sqrt{\left[\frac{\gamma_T^4}{(1+\alpha+i\beta)^2}+4\gamma_L^2\right]}} \quad (35)$$

To find the polarizations corresponding to the two values of the complex refractive index cq given by (35), we note that, on substituting from (28) in (32), we have

$$\frac{P_z}{P_y}=\frac{-i\gamma_L}{[1/(c^2q^2-1)]-(\alpha+i\beta)} \quad . \quad . \quad (36)$$

and thus

$$\frac{H_y}{H_z}=\frac{i\gamma_L}{[1/(c^2q^2-1)]-(\alpha+i\beta)} \quad . \quad . \quad (37)$$

The two formulæ (35) and (37) are therefore the representative equations for the magneto-ionic theory in terms of a ray treatment, and their elucidation and application constitute one of the most important problems in connection with present-day wireless theory. We proceed to a very brief discussion of them.

Let us write

$$4\pi Ne^2/m = p_0^2;\ H_Le/(mc) = p_L;\ \text{and}\ H_Te/(mc) = p_T$$

We then have

$$\alpha = -(p^2/p_0^2) - \tfrac{1}{3}; \qquad \beta = p\nu/p_0^2;$$
$$\gamma_L = pp_L/p_0^2 \quad \text{and} \quad \gamma_T = pp_T/p_0^2$$

so that, on substitution in the general formula (35) we have

$$c^2q^2 = (\mu - i\kappa/p)^2 = 1 - \frac{2p_0^2}{2(p^2+\frac{1}{3}p_0^2-ip\nu)-\frac{p^2p_T^2}{p^2-\frac{2}{3}p_0^2-ip\nu}\mp\sqrt{\left[\frac{p^4p_T^4}{(p^2-\frac{2}{3}p_0^2-ip\nu)^2}+4p^2p_L^2\right]}} \quad . \quad (38)$$

where μ is the refractive index and κ the absorption coefficient.

We may note also that if the polarization term ($\frac{1}{3}$) in the expression for α is not included we have, in place of (38),

$$c^2q^2 = (\mu - i\kappa/p)^2 = 1 - \frac{2p_0^2}{2(p^2-ip\nu)-\frac{p^2p_T^2}{p^2-p_0^2-ip\nu}\mp\sqrt{\left[\frac{p^4p_T^4}{(p^2-p_0^2-ip\nu)^2}+4p^2p_L^2\right]}} \quad . \quad . \quad (39)$$

A full interpretation of these equations cannot be attempted here, though some approximations which are useful in practical work are given in the Appendix. Some general results may, however, be mentioned. Equations (38) or (39), together with the polarization equation (37), show that there are propagated, in general, two waves of different phase-velocity, polarization, and absorption. The wave corresponding to the lower sign in (38) or (39) may be called the ordinary ray, since its characteristics are not relatively very much influenced by the magnetic field, while the wave corresponding to the upper sign may be referred to as the extraordinary ray since it exhibits the phenomenon of quasi-resonance with the characteristic gyroscopic frequency conditioned by the earth's magnetic field. The ordinary ray is, in general, less absorbed than the extra-ordinary ray. The polarizations of the magnetic forces in the two waves are similar ellipses the major axes of which are at right angles. For a direction of propagation making an acute angle with the positive direction of the magnetic field the polarization of the ordinary wave is left-handed and that of the extra-ordinary wave right-handed.

The refractive index for the ordinary ray becomes zero when the condition $(1+\alpha)=0$ is reached. The refractive index for the extra-ordinary ray becomes zero when either of the conditions $(1+\alpha)=\pm|\sqrt{(\gamma_T^2+\gamma_L^2)}|$ is satisfied. Two illustrative examples may be cited. For vertical incidence in the British Isles and 80-m waves the condition $(1+\alpha)=-|\sqrt{(\gamma_T^2+\gamma_L^2)}|$ is reached first for the extra-ordinary ray, so that it is reflected first and reaches the ground as a right-handed component, the other ray travelling further into the layer until the condition $(1+\alpha)=0$ is reached, when it too is reflected On the other hand, for 400-m waves the conditions are reversed, for the ordinary ray is reflected at a lower level than the extra-ordinary ray, since the condition $(1+\alpha)=0$ is satisfied for the former before the condition $(1+\alpha)=+|\sqrt{(\gamma_T^2+\gamma_L^2)}|$ is reached for the latter.

(7) The Nature of the Ionization.

Material evidence concerning the nature of the electrical carriers in the two reflecting regions is derivable from the experiments on the polarization of downcoming waves and on the "splitting" of echoes. For the upper F region the observations of Builder and myself* on magneto-ionic double refraction leave little doubt that the electrical carriers there are of electronic mass, since the refractive process is so profoundly influenced by the earth's magnetic field. In the case of the lower region, although the doubling of echoes has been observed, its cause cannot be attributed to the influence of the earth's field with quite the same certainty as in the case of the upper region. But the characteristic polarizations exhibited by waves reflected from the lower region certainly indicate the presence of at least some electrons.

In this connection it should be pointed out that the formulæ describing both the refractive and absorptive processes involve essentially the quantity $\Sigma(N/m)$ where N is the number of carriers of mass m. Where both electrons and ions (of numbers N_e and N_i, and masses m_e and m_i) are present the corresponding quantity is $(N_e/m_e + N_i/m_i)$. For the upper region we know that

* See Bibliography, (30).

$N_e/m_e > N_i/m_i$. For the lower region we know that N_e/m_e is greater than zero, but we are not yet quite certain of the relative values of N_e/m_e and N_i/m_i.

The fact that there are two reflecting regions suggests that there are two regions in which $\Sigma(N/m)$ reaches a maximum. This means that we can say that there are two regions in which the conductivity is a maximum, since the conductivity is determined by the same quantity. But even if we know approximately the way in which $\Sigma(N/m)$ varies with height, we have no very definite evidence as to the way in which N_e/m_e and N_i/m_i vary separately.

(8) The Nature of the Ionizing Agencies.

The evidence of wireless transmission points quite clearly to ionizing agencies of solar origin. The correlation of phenomena with sunset and sunrise show clearly that, for the normal processes, the greater part of the radiation in question travels in straight lines. Chapman has given reasons for assuming that the lower region is ionized by neutral particles and the upper region by ultra-violet light. At a recent Geophysical Discussion at the Royal Astronomical Society* I mentioned the possibility of deriving during a solar eclipse information concerning the nature of the ionizing agency, and this was further discussed by Chapman. Because of the difference in velocity with which ultra-violet light and moving particles travel, it turns out that there are important differences in the incidence in time and place for what may be called the "optical eclipse" and the "corpuscular eclipse" when the moon cuts off the solar stream from the earth.

In the solar eclipse of 1927 in Great Britain the results obtained have been interpreted as supporting the view that ultra-violet light is partly operative in the lower region, since a partial return to night-time conditions was experienced round about optical totality. But on that occasion no observations were made during the time when the "corpuscular eclipse" was to be expected. For the eclipse on the 31st August, 1932, arrangements have been made to carry out observations both on the track of optical totality and also at stations situated on or near the belt of the "corpuscular eclipse."

Most of the available evidence shows that the agency which causes magnetic storms and also the excess ionization beyond the ordinary diurnal value on disturbed days is corpuscular in character. This excess ionization is to be found chiefly in the lower region.

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* See Bibliography, (31).

APPENDIX.

The somewhat complicated formula (35) may be simplified for certain practical cases. Let us suppose, for example, that the frequency of electron collisions with gas molecules is small compared with the electric wave frequency. We then have $\frac{\beta}{|\alpha|} \ll 1$. Also if the ionization is not too dense we also have $\beta^2 \ll (1 + \alpha)^2$.

Let us now write

$$\left(\mu - \frac{ic\kappa}{p}\right)^2 = 1 + \frac{1}{X + iY} \quad . \quad . \quad . \quad (1a)$$

so that $$\mu^2 - \frac{c^2\kappa^2}{p^2} = 1 + \frac{X}{X^2 + Y^2} \quad . \quad . \quad . \quad (2a)$$

and $$\frac{2c\kappa\mu}{p} = \frac{Y}{X^2 + Y^2} \quad . \quad . \quad . \quad . \quad (3a)$$

In our attempt to find the values of μ (the refractive index) and κ (the absorption coefficient) we note that $\kappa c/p$, which represents the exponential absorption factor for a length of path $\lambda/(2\pi)$, must be very small compared with unity, except for conditions near $\mu^2 = 0$. If this were not the case, the absorption would be such that the waves would never reach the ground in measurable intensity. We thus can write

$$\mu^2 = 1 + \frac{X}{X^2 + Y^2} \quad . \quad . \quad . \quad . \quad (4a)$$

and $$\frac{\kappa c}{p} = \frac{1}{2\mu} \cdot \frac{Y}{X^2 + Y^2} \quad . \quad . \quad . \quad . \quad (5a)$$

If now X and Y can be found, μ and κ can be determined from (4a) and (5a). In the case considered below, it can further be shown that $Y^2 << X^2$, so that (4a) and (5a) become

$$\mu^2 = 1 + 1/X \quad . \quad . \quad . \quad . \quad (6a)$$

$$\frac{\kappa c}{p} = \frac{1}{2\mu} \cdot \frac{Y}{X^2} = \frac{(1 - \mu^2)^2}{2\mu} Y \quad . \quad . \quad . \quad (7a)$$

Now, according to (35), we have

$$X + iY = (\alpha + i\beta) - \frac{\gamma_T^2}{2(1 + \alpha + i\beta)} \pm \sqrt{\left[\frac{\gamma_T^4}{4(1 + \alpha + i\beta)^2} + \gamma_L^2\right]} \quad . \quad (8a)$$

If we assume that $\beta^2 << (1 + \alpha)^2$, it is possible to equate separately the real and imaginary parts so that we have

$$X = \alpha - \frac{\gamma_T^2}{2(1 + \alpha)} \pm \sqrt{\left[\frac{\gamma_T^4}{4(1 + \alpha)^2} + \gamma_L^2\right]} \quad (9a)$$

and

$$Y = \beta\left(1 + \frac{\gamma_T^2}{2(1 + \alpha)^2} \mp \frac{\gamma_T^4}{2(1 + \alpha)^2\sqrt{\left[\gamma_T^4 + 4\gamma_L^2(1 + \alpha)^2\right]}}\right) \quad (10a)$$

so that from (6a), (7a), (9a), and (10a), we can determine the values of μ and κ directly when α, β, and γ, are specified. Let us take the case in which the polarization term is neglected. For convenience in computation it is useful to employ the following notation. Let

$$\frac{4\pi Ne^2}{mp^2} = x, \quad \frac{H_L e}{mcp} = y_L, \quad \frac{H_T e}{mcp} = y_T, \quad \text{and} \quad \frac{\nu}{p} = z$$

Using (6a) and (9a) we may therefore write the expression for the refractive index

$$\mu^2 = 1 - \frac{2x}{2 - \frac{y_T^2}{1 - x} \mp \sqrt{\left[\frac{y_T^4}{(1 - x)^2} + 4y_L^2\right]}} \quad . \quad (11a)$$

which shows that, to our degree of approximation, the effect of friction on the phase velocity is negligible. Similarly, using (7a) and (10a), we find

$$\frac{\kappa c}{p} = \frac{(1 - \mu^2)^2}{2\mu}\left\{\frac{z}{x}\left(1 + \frac{y_T^2}{2(1 - x)^2} \mp \frac{y_T^4}{2(1 - x)^2\sqrt{\left[y_T^4 + 4y_L^2(1 - x)^2\right]}}\right)\right\} \quad . \quad . \quad . \quad . \quad (12a)$$

Corresponding formulæ may easily be derived from (38) in which the local polarization effect is taken into account. It is important to note, when plotting curves illustrating the relation between μ^2 and N, that x is proportional to the ionization.

DISCUSSION ON

"METAL-CLAD SWITCHGEAR, AUTOMATIC PROTECTION, AND REMOTE CONTROL, WITH PARTICULAR REFERENCE TO DEVELOPMENTS DURING THE LAST SEVEN YEARS."*

ADDITIONAL COMMUNICATION TO THE DISCUSSION.

Dr. J. Kopeliowitch and **Mr. J. K. Brown** (*Switzerland; communicated*): In Section (2) (xvi), "Switching Capacity," and Appendix I the author deals with the problem of the interpretation of oscillograms from actual test-results. In view of the number of testing plants in existence it is of importance that an international agreement be reached with regard to the calculation of the rupturing capacity and the conditions for carrying out short-circuit tests on circuit breakers. On page 301, in discussing the rating of circuit breakers according to B.S.S. No. 116—1929, the author points out that for Table 4 the recovery voltage is not prescribed. The table gives for a specified kVA rating the current-breaking capacity at standard voltages; however, it is stated on page 20 of B.S.S. 116 ["Method of Interpreting Test Records" 72 (iii)] "the kVA broken shall be calculated in the usual manner from the recovery voltage observed after the extinction of the arc in all phases, and from the breaking current." Consequently it must definitely be understood that for short-circuit tests the rated current must be interrupted with a recovery voltage equal to the rated voltage, in order to obtain the kVA given in Table 4.

The author's reference on page 301 to rating, performance, and selection is vague and indefinite. The terms should be considered in the reverse order, i.e. selection, performance, and rating. In 1931 the Swiss Committee of the Paris Conference on Large Distribution Systems prepared a report on the calculation of the short-circuit capacity of networks and the factor of safety to be considered when selecting circuit breakers.† These two factors are of fundamental importance with regard to selection. The conclusions drawn by the Committee were that the responsibility for the determination of the rupturing capacity, P_g, rests with the purchaser, while the manufacturer must guarantee that the circuit breaker can rupture the value of P_g specified. The selection then depends on the voltage and rupturing capacity. Rating and performance should be interdependent, the rating of the breaker being derived from the actual performance during short-circuit tests. As a result the conditions for such tests must be carefully investigated and should conform with practical conditions as far as possible. To compare the performances and, consequently, the ratings of different types of circuit breakers, it is essential that the specifications for short-circuit tests should be agreed upon internationally. The necessity for such an agreement has been pointed out several times previously, but it appears that as a result of the experience gained in high-power test plants the opinion is now almost universal. The ideal solution of the problem would be to establish an international testing circuit as suggested by the author; however, owing to the different characteristics of the plants already in existence, such an ideal solution is impossible and also unnecessary. The alternative is to draw up specifications based on the proposals of the I.E.C. Sub-Committee No. 17 similar to those given in the table on pages 319 and 320 of the paper. This table cannot be regarded as complete. Other regulations must be laid down, e.g. the use of abnormal connections necessitated by inadequate testing-plant capacity or the cost of acceptance tests. The following remarks apply only to the clauses suggested by the author.

(ii) (*b*) The author states that the voltage used to calculate performance shall be the rated voltage. This should only be so when the rated voltage equals the recovery voltage.

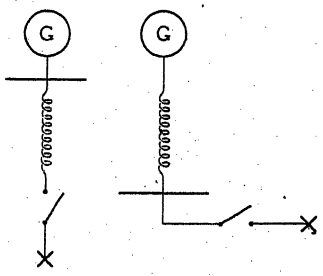


FIG. BB.

(iii) It is not clear how the author has determined a mean value of 80 per cent for different systems. For a fault as shown in Fig. BB where a current-limiting reactor is used (a case often met with in practice), the recovery voltage following a short-circuit would be almost 100 per cent. To compromise between the power factor and the recovery voltage, as suggested at the bottom of page 318, would only lead to further complications. It is safer to test with a recovery voltage equal to the rated voltage; this allows a factor of safety in particular cases. For a breaker situated near the generating station the voltage decrement would under certain conditions be fairly large, and hence the stress imposed on the breaker would be reduced. For a breaker at the end of a long feeder the recovery voltage would be practically 100 per cent, but in this case the additional electrostatic capacitance of the network would reduce the natural frequency of oscillation of the system and hence the stress on the breaker. The precise difference is difficult to estimate for all operating conditions, and varies considerably for individual systems.

(iv) The present practice of calculating the recovery voltage as the R.M.S. value of the voltage for the first

* Paper by Mr. H. W. CLOTHIER (see page 285).

† Report of Committee on Circuit Breakers, International Conference on Large Distribution Systems, Paris, 1931.

or second half-cycle at normal frequency after the interruption of all phases seems to be entirely satisfactory. Extrapolation back exactly to the final zero point of the current in the last phase to clear is not necessary, as the increase in voltage for the first few half-cycles is small. In addition, when a low- or high-frequency oscillation is superimposed on the normal voltage the evaluation will be more difficult and less accurate than the present method.

(vi) The question of breaking current will be discussed later.

on the voltage-zero line between the current and voltage for the same phase. This is expressed in degrees by means of the time scale and the corresponding value of $\cos\phi$ obtained from mathematical tables. The degree of asymmetry of the current is also given (column 3) for the first half-cycle after the commencement of the short-circuit; the value is expressed as a percentage, i.e. the ratio of the d.c. component I_c to the R.M.S. value I_r of the a.c. component. It may be seen that for test K 67 the average value for both phases is 0·010. The repeat test under identical conditions (K 68) gave

TABLE C.

Oscillogram No.	Phase	Percentage asymmetry of current $(I_c/I_r) \times 100$		Consecutive voltage zeros 1	2	3	4	Mean value of $\cos\phi$
K 67* Scale:— $\frac{1}{100}$ sec. = 40 mm	Red	111	Distance, mm	18·6	20·1	18·8	21·9	—
			ϕ	83·7°	90·5°	84·6°	98·5°	—
			$\cos\phi$	0·110	− 0·009	0·094	− 0·148	0·012
K 67* Scale:— $\frac{1}{100}$ sec. = 40 mm	Yellow	97	Distance, mm	20·5	18·6	21·3	19·2	—
			ϕ	92·4°	83·7°	96·0°	86·4°	—
			$\cos\phi$	− 0·042	0·110	− 0·105	0·063	0·007
K 68* Scale:— $\frac{1}{100}$ sec. = 40 mm	Red	124	Distance, mm	19·3	16·9	20·2	17·0	—
			ϕ	86·8°	76·0°	91·0°	76·5°	—
			$\cos\phi$	0·056	0·242	0·017	0·233	0·137
K 68* Scale:— $\frac{1}{100}$ sec. = 40 mm	Yellow	68	Distance, mm	18·3	21·0	18·8	20·0	—
			ϕ	82·4°	94·5°	84·6°	90·0°	—
			$\cos\phi$	0·132	− 0·078	0·094	0·000	0·037
O 8/3* Scale:— $\frac{1}{100}$ sec. = 10 mm	Yellow	85	Distance, mm	4·8	4·8	4·8	4·7	—
			ϕ	86·5°	86·5°	86·5°	84·7°	—
			$\cos\phi$	0·061	0·061	0·061	0·093	0·069
O 8/3* Scale:— $\frac{1}{100}$ sec. = 10 mm	Blue	131	Distance, mm	4·3	4·9	4·0	4·5	—
			ϕ	77·5°	88·3°	72·0°	81·0°	—
			$\cos\phi$	0·216	0·030	0·309	0·156	0·178

* The tests were carried out with a normal supply frequency of 50 cycles per sec.

(vii) The frequency of supply cannot definitely be fixed at 50 cycles, on account of non-uniformity in different countries. It may be pointed out that the difference between 40 and 60 cycles has apparently a negligible effect on the breaker.

(viii) Table C shows the results of the calculations of the power factor from oscillograms for three different tests. The power factor has been calculated for four successive voltage zeros after closing the circuit, by superimposing the voltage before the short-circuit on the current wave; this gives more accurate results than would be obtained by using the recovery voltage. In order to show the errors that arise in the calculation, all the values have been given. In the fourth column the distance "mm" represents the distance measured

$\cos\phi = 0·087$. The difference between these values is 770 per cent. Before the tests were carried out the calculated value of $\cos\phi$ was 0·05. The oscillogram in which the time scale is considerably reduced gives also large divergence of results when compared with the calculated value (0·05). The average value for both phases is 0·123, and the difference 158 per cent. The above calculations, i.e. the mean value in the last column of Table C, give more exact results than those from the author's proposal, as the values were calculated from a number of points, not only from the current zero immediately preceding the opening of the contacts. This point is, however, relatively unimportant, as, for all practical purposes, it is sufficient to specify that the power factor of the test circuit must be less than 0·3.

In addition to the divergence of results obtained from the oscillograms used, a further error is introduced when it is not possible to draw the contour curve of the current. Such a case is shown in Fig. 73 of the author's paper. On the other hand, when the current is symmetrical it may be found that the difference between the values for consecutive current zeros is reduced. It is therefore to be recommended that wherever possible the value of cos ϕ should be derived from tests when the d.c. component is small.

(ix) and (x) With regard to the problem of earthing, it is difficult to understand whether the author implies that at and above 66 000 volts the neutral point on the supply and test side should be definitely earthed. When both the short-circuit point and the neutral point are earthed the restriking voltage per pole would be equal to the phase voltage. When the neutral point on either the supply or test side is unearthed, then the restriking voltage for all phases would theoretically be $1{\cdot}5 \times$ phase voltage. Apart from the high-frequency oscillations, the voltage stress on all three phases would be 50 per cent higher than when the neutral point and short-circuit point are earthed. This case is often met with in practice, so that it is necessary to state either that for all voltages both the short-circuit point and the neutral point on the supply side cannot be earthed, or that the tests are to be carried out according to the demands of practice.

(x) (*b*) The statement in this clause appears to be contrary to the interpretation of Clause (iv) (Restriking Voltage). In order to control the natural frequency of oscillation of the circuit and hence the rate of rise of the recovery voltage, it is necessary to include in the test circuit definite values of inductance and capacitance. This is stated in Clause (iv), which is in opposition to Clause (x *b*). The influence of the wave-form of the recovery voltage or restriking voltage on the operation of circuit breakers is of importance; articles dealing with this problem have already been published.* Before specific values of frequency and voltage-rise can be given for specifications, further investigations are necessary, particularly with regard to high-tension systems and different types of breakers. Ultimately, agreement must be reached in order that circuit breakers may be rated according to their performance under similar test-conditions. At the present time the divergence between test-conditions is principally due to the rate of rise of the voltage. Other factors governing the severity of test, such as methods of earthing, normal supply frequency, and power factor can be made the same for the different short-circuit testing plants.

(xi) (2) With regard to the generator voltage, it is impossible to lay down definite regulations. The tests must be so arranged that for the required voltage and current the requisite conditions for power factor and earthing, etc., are fulfilled. The author's suggestion that between 3 300 and 22 000 volts the breaker must be connected directly to the generating plant is not feasible, as there are already several plants in existence that cannot fulfil this specification. Experience has shown that high-voltage generators are not necessarily the most practical for short-circuit testing plants.

(xi) (*d*) The length of the connections between the circuit breaker under test and the source of short-circuit power can only be determined by the general lay-out of the test plant and is of no practical importance.

With regard to the calculation of the breaking current, it may be remarked that there is more diversity of opinion than for any of the other factors mentioned in the author's proposals. On the Continent it is standard practice to neglect the d.c. component of the current, whereas in England and America the R.M.S. value of the breaking current is calculated from the a.c. and d.c. components. In order to understand this problem it is essential to consider separately making and breaking currents. The making-current test is carried out in order to show that the breaker structure and contact arrangement are suitably designed to withstand the electro-dynamical forces set up by the short-circuit current. The force is determined from the peak value of the current and consequently should be calculated as the maximum current in the major half-cycle immediately after the circuit is closed. On the other hand the breaking current determines the combined electrical and mechanical performance of a breaker with regard to the pressure generated and the resultant stress in the structure when opening under short-circuit conditions. The two factors influence the breakers in different ways, so that a circuit breaker should have definite and distinct ratings for making and breaking capacities. For a network it is possible to derive the maximum making capacity from the rupturing capacity; however, the two values must not be interchanged or confused. The making capacity of an oil circuit-breaker should be determined from tests with maximum asymmetrical current, either single- or 3-phase, irrespective of the test voltage. The breaking capacity must be derived from tests with symmetrical current and will consequently be less than the making capacity. If I_M and I_B are the making and breaking currents respectively, then I_M (peak amps.) $\simeq 2{\cdot}65\ I_B$ (R.M.S. amps.).

The report of I.E.C. Committee No. 17 (1930) on oil circuit-breakers and switches states, in Clause 6, that the d.c. component of the current must be less than 30 per cent of the R.M.S. value of the a.c. components. This is due, as quoted by the author, to the low value of the restriking voltage when the current is asymmetrical. Oscillograms have been published showing the influence on the interruption process.* This is of particular importance for medium- and low-tension breakers. The only claim that the d.c. component must be considered in the calculation of the breaking current is its possible influence on the rate of generation of the gas bubble and the corresponding increase of stresses in the structure. For the major half-cycle of an asymmetrical current wave the amount of gas will be more than that which is generated during the minor half-cycle. The total amount generated during both half-cycles may be the same as produced by a symmetrical current having the same a.c. component during the same time-interval. Consequently this factor can

* J. Kopeliowitch and J. K. Brown: "Influence of the Wave-Form of the Recovery Voltage on the Operation of Circuit Breakers," *Electrician*, 1932, vol. 108, p. 93; also R. H. Park and W. F. Skeats: "Circuit-Breaker Recovery Voltages," *Transactions of the American I.E.E.*, 1931, vol. 50, p. 204.

* J. Kopeliowitch: "International Standardization of Oil Circuit-Breakers: Definition of Rupturing Capacity," *Revue Générale de l'Électricité*, 1928, vol. 24 p. 625; also R. H. Park and W. F. Skeats: *loc. cit.*

only be considered when a breaker is always able to interrupt the short-circuit in one half-cycle. For an odd number of half-cycles the amount of gas generated by an asymmetrical current can be more or less than with a symmetrical current. In practice it is thus impossible to consider the d.c. component, as a breaker is practically never called upon to interrupt the short-circuit during the period when the d.c. component is a maximum. By the time the contacts begin to separate the current is nearly symmetrical and the effect of the d.c. component is almost negligible. As a result, the difference between the symmetrical and unsymmetrical currents on the development of gas would be of no importance. In a testing plant the effects are different, as it is usual to release the contacts shortly after the short-circuit begins, in order to obtain the maximum rupturing capacity of the plant. As a result, in extreme cases the contacts can be made to separate during the first or second half-waves. The d.c. component will be a maximum in this case, so that if the rupturing current is calculated according to the B.S. Specifications the corresponding rupturing capacity will be considerably larger than when calculated from the I.E.C. proposals. As pointed out above, it is only permissible to include the d.c. component in the calculation of the rupturing current when the breaker is *always* able to interrupt the short-circuit in one half-cycle. Owing to the fact that the restriking voltage in this case is comparatively small, the effect of the displacement of the current reduces the stress on the breaker and will help directly in extinguishing the arc. Assuming maximum asymmetrical current in one phase the making current $= 1{\cdot}8\sqrt{2}I_a$ amperes, where I_a is the R.M.S. value of the a.c. component for the first half-cycle; the corresponding peak value of the current in the other two phases $= 1{\cdot}35\sqrt{2}I_a$. Owing to the fact that the making current is usually given as the peak value in amperes, the following ratios will be determined for the peak value "making" current and the R.M.S. value of the "breaking" current. Using the same notation as above, the maximum value of the current that can be used in the calculation of the 3-phase breaking capacity, that is, the mean value of the current for all three phases *considering maximum asymmetrical current*, is $1{\cdot}33\ I_a$ amperes (R.M.S.). The rupturing capacity according to the author's proposal is $1{\cdot}33\ I_a$ amperes if the contacts are separated in the first half-cycle (recovery voltage 100 per cent).

$$\text{The ratio } \frac{\text{making capacity}}{\text{breaking capacity}} = \frac{4{\cdot}5\sqrt{2}I_a}{3 \times 1{\cdot}33I_a} = 1{\cdot}59$$

Neglecting the d.c. component, the rupturing capacity is I_a amperes and

$$\text{the ratio } \frac{\text{making capacity}}{\text{breaking capacity}} = \frac{4{\cdot}5\sqrt{2}I_a}{3I_a} = 2{\cdot}12$$

Finally, assuming that the separation of the contacts takes place after a time-interval when the d.c. component is reduced to less than 30 per cent of the a.c. component, the ratio will be approximately

$$\frac{4{\cdot}5\sqrt{2}I_a}{3 \times 0{\cdot}8I_a} = 2{\cdot}65$$

A further example of the difference between the various specifications may be obtained directly from the oscillogram and table given in the author's Fig. 73 (Test 5723). The recovery voltage = 2 960 volts per phase; voltage before short-circuit = 3 640; voltage decrement = 81·2 per cent; breaking current (mean value including the d.c. component) = 97 000 amps.; R.M.S. value of a.c. component = 85 000 amps. Breaking capacity from British Standard Specifications = 890 000 kVA, calculated with voltage before the short-circuit = 1 060 000 kVA; from the Swiss Specifications = 670 000 kVA. The tests were carried out on a breaker with a rupturing capacity of 1 000 000 kVA. According to the author's interpretation of B.S.S. No. 116 the capacity is thus obtained, whereas the rupturing capacity calculated with the a.c. component of the current and the recovery voltage = 670 000 kVA. This gives a difference of 58 per cent. From the oscillograms it is impossible to evaluate the rupturing capacity according to the I.E.C. proposals, because the d.c. component is considerably in excess of 30 per cent. It is in the interest of both manufacturers and supply undertakings to eliminate these divergencies in the interpretation of rupturing capacities and, therefore, the rating of circuit breakers.

Mr. H. W. Clothier (*in reply*): The communication from Dr. Kopeliowitch and Mr. Brown is very welcome, because it may be taken as a typical Continental view, whereas the discussion already published outlines the British and the American points of view. I will therefore reply separately in detail to the Continental view.

International Standardization.

(*a*) *Requirements.*—I agree with Dr. Kopeliowitch and Mr. Brown that it is most important to obtain international agreement upon standard conditions for short-circuit tests of circuit breakers, and it was with this object that I put forward my proposals for discussion in Great Britain prior to their international discussion. I think that they require only slight extension to cover the points raised by Dr. Kopeliowitch and Mr. Brown, and so to provide the required international standard conditions, which must indirectly standardize suitable test-circuits. In my opinion such standardization is the primary factor in establishing the performance of circuit breakers, on the basis of which ratings can be assigned to them under clearly understood conditions. Dr. Kopeliowitch and Mr. Brown refer to the proposal that the purchaser should be responsible for determining the rupturing capacity required, and the manufacturer for guaranteeing that the circuit breaker has the specified rupturing capacity; but I go further, with a proposal, which does not seem in any way vague or indefinite, to explain to the purchaser what is meant by the rating assigned to a circuit breaker, so that he may select for himself with greater confidence to meet his service conditions.

(*b*) *Recovery Voltage.*—I am at variance with the view of Dr. Kopeliowitch and Mr. Brown that recovery voltage should be used as a multiplier for calculating the performance of a circuit breaker in kVA, because I prefer to treat recovery voltage, like power factor, as a condition of severity. To multiply a current value measured at the instant of contact separation by a voltage

that exists at an entirely different instant of time gives a product that is physically meaningless. In my opinion the only quantities that should be used to express the performance of a circuit breaker at a given rated voltage are values of currents applied under prescribed conditions of severity. Although B.S.S. No. 116–1929 states at present (July 1932) that the "kVA broken shall be calculated in the usual manner from the recovery voltage observed after the extinction of the arc in all phases, and from the breaking current," there is no clause specifying how the value of the recovery voltage shall be obtained, and consequently a revision of the specification is officially under consideration on the basis of treating recovery voltage as a condition of severity, rating by current at a given voltage, and retaining kVA only as a nominal rating, given for convenience in selection, and representing the product of the rated voltage, the breaking current, and the appropriate phase-factor, in compliance with the existing Clause 46.

The question therefore becomes one of establishing a minimum value of recovery voltage as a standard condition of severity, and Dr. Kopeliowitch and Mr. Brown inquire how the value of 80 per cent specified in Proposal (iii) on page 319 of the paper was reached. Consider first a large circuit breaker in close proximity to generating plant. This will be subjected to a recovery voltage of the order of 60 to 80 per cent, depending upon the generator characteristics and the duration of the short-circuit, and for this condition of service the proposed 80 per cent errs on the high side. Dr. Kopeliowitch and Mr. Brown indirectly confirm the 80 per cent in their remarks on breaking current and making current, because they infer that the alternating component of the current at the instant of contact separation has fallen to 80 per cent of its value at the incidence of the short-circuit; and thus they indicate that they anticipate an active voltage of 80 per cent at the instant of contact separation, and consequently a recovery voltage of a similar order of magnitude. I agree that for a small circuit breaker remote from generating plant the recovery voltage will approach 100 per cent; but at the test plant, when such a circuit breaker is tested, a similar increase in recovery voltage occurs automatically owing to the added reactance and resistance in the test circuit, because the power taken from the generating plant is small in comparison with what it can develop when testing large circuit breakers for service close to a generating station. It is on this account that Proposal (iii), on page 319 of the paper, recommends that the specified value of 80 per cent for recovery voltage should be a minimum. I submit that Proposal (iii), to measure the recovery voltage at the critical instant of time following arc extinction, describes a reasonable method to adopt; but I should be prepared, in furtherance of international agreement, to support a suggestion to measure it on the basis proposed by Dr. Kopeliowitch and Mr. Brown. The difference between the two results would generally be very small.

(*c*) *Power Factor.*—Dr. Kopeliowitch and Mr. Brown prefer to predetermine the short-circuit power factor by calculation, in accordance with my Proposal (viii) (*c*) on page 320 of the paper. Appendix I includes this method, for the reasons they advocate; but it also includes a method for checking the predetermined values from actual test results; and it must not be forgotten that the values of the short-circuit resistance and reactance of the test circuit, which enter into the preliminary calculation, are only obtainable accurately from short-circuit tests, and an oscillograph record is the most convenient means of indicating the physical relationship between the current and the voltage in a given test.

It seems to me misleading that Dr. Kopeliowitch and Mr. Brown should give 770 per cent as the error resulting from comparing two oscillograph records (presumably of 3-phase tests), because they have arrived at this by comparing extreme erroneous measurements of cos ϕ in two separate phases. Some of the angles given in their table are over 90°, and this indicates at once that results have been distorted by errors of measurement. If, however, all the angles given for two phases in their tests Nos. K 67 and K 68 are averaged by being added together and divided by 16, the average angle is 87° 21′, and this corresponds very closely to the calculated power factor of 0·05, which is the cosine of 87° 8′. The distances in millimetres given in Tests Nos. K 67 and K 68, instead of being practically identical, or, as is more probable, progressive in value, actually show a regular fluctuation, one possible explanation of which is that the imaginary zero line (representing the d.c. component) has been drawn slightly displaced on the oscillograph record. If the mean distances in millimetres of consecutive half-cycles are taken, to compensate for errors in the zero line, it is found that they gradually increase, and so indicate the expected slight fall in the speed of the test generator. On the assumption that 90° (electrical) corresponds to 20 mm at the incidence of the short-circuit, and that at each subsequent voltage zero the distances increase in proportion to the fall in speed of the generator, the scale will increase progressively from 20 mm at the incidence of the short-circuit to slightly greater values at the subsequent zero points. If the mean value of the first two distances in millimetres given for voltage zeros (1) and (2) is divided by the scale appropriate to the particular instant of time, and if this is assumed to be 20 mm, the phase angle on the red phase in Test No. K 67 is 87°, and that on the yellow phase is 88°. The average of these two angles is 87° 30′, which again compares closely with the angle of 87° 8′, corresponding to the calculated power factor of 0·05 lagging.

Dr. Kopeliowitch and Mr. Brown, after proving their difficulty in making an accurate measurement, suggest that it is sufficient to specify that the power factor of the test circuit must be less than 0·3; but this leaves entirely unspecified how it is to be ascertained in practice. Admittedly, the power factor is difficult to measure in an oscillogram like that of, for example, Fig. 73 of the paper; but in regular testing, which includes many records with long as well as short arcing periods, both symmetrical and asymmetrical, the more accurate measurements obtainable on the long ones do give a reasonable check on the values of phase angles for the whole. Incidentally, the value of 0·3 lagging, proposed for the power factor in the communication, is in my opinion too high for the standard test circuit. I consider the 0·15 lagging power factor recommended by

the International Electrotechnical Commission to be of an appropriate order of magnitude, but the more severe British value of 0·1 lagging is a still better standard.

The vital point is that we should understand what is meant when we talk of power factor, in respect of either a single-phase or a 3-phase short-circuit test. The power factor is based on angles measured as accurately as is physically possible on each phase at the point of separation of the arcing contacts, and for a 3-phase short-circuit it is based on an average of the three angles. This is the primary intention of the definition given in Appendix I. I should have welcomed some suggestion for improvement of the definition or of the proposed method of measurement.

I am indebted to Mr. J. A. Harle for a particularly helpful method (described in Appendix VII below) of obtaining, by measurement on an oscillograph record, the power factor of an asymmetrical phase of an actual short-circuit, on the lines of Proposal (viii) (*c*) of Appendix I. It is applicable to series test-circuits, but not to circuits in which there are parallel paths having different time-constants; and therefore its scope for general use in field tests may be limited by reason of the interconnections of the network.

(*d*) *Earthing, Frequency, and Short-Circuit.*—The proposals in the paper cover British practice, which, for lower-voltage networks, is usually to earth the neutral point through a resistance, or, alternatively, to insulate it, whereas, for networks working at 66 000 volts or more, it is usual to earth the neutral point solidly. Continental practice agrees with Proposal (ix) (1) of the paper in insulating the neutral points of systems below 66 000 volts, and it also agrees with Proposal (ix) (2) partially, because it tends to earth the neutral points of systems working at the very highest voltages; but there is an intermediate range over which it insulates the neutral point, contrary to Proposal (ix) (2). Circuit breakers intended for operation within this range are usually constructed as sets of individual single-phase units, and therefore lend themselves very conveniently to single-phase testing. Further, since the bulk of switchgear increases very rapidly with its rated voltage, it is important from an economic point of view to keep down the quantity of equipment under test; and again, with large circuit breakers, single-phase testing allows a relatively small amount of testing plant to be adequate. These economic considerations cannot be ignored, because of their influence on the total cost of high-voltage switchgear; and, taking everything into account, I would propose generally that circuit breakers intended for use on networks working at and above 66 000 volts, but still retaining insulated neutral points in spite of the increasing modern tendency towards some form of earthing the neutral point, shall still be tested under standard conditions, with their neutral points solidly earthed, but shall have their performance results reduced by, say, 25 per cent and their ratings based on these reduced values.

Proposal (xi) (page 320 of the paper) could easily be modified to correspond to Continental practice and test-plant facilities by connecting the apparatus under test to the test plant as follows:—

(1) Below 3 300 volts, to transforming plant.
(2) From 3 300 volts to 11 000 volts, to generating plant.
(3) Above 11 000 volts, to transforming plant.

Since Dr. Kopeliowitch and Mr. Brown find that the effect on the circuit breaker of a change of frequency between 40 and 60 cycles per sec. is negligible, it would be best to establish the mean value of 50 cycles per sec. as the standard. It is provided in the paper that the frequency actually used, if not standard, shall be stated on the test certificate.

(*e*) *Restriking Voltage.*—I would point out that the resistance and reactance in the test circuit referred to in Proposal (iv) (page 319) are to be used in series with the apparatus under test, primarily for the purpose of regulating the value of the short-circuit current, whereas Proposal (x) (*b*) (page 320) prohibits their use in parallel with the apparatus under test, when they would serve as a means of reducing the severity of the test. I would refer to Mr. Leeson's contribution (page 336) as a reply to the points raised by Dr. Kopeliowitch and Mr. Brown about the length of the connections used in the test plant and the rate of rise of restriking voltage.

(*f*) *Current Measurement.*—Dr. Kopeliowitch and Mr. Brown discuss at considerable length the question of whether the breaking current should be determined only from the a.c. component of the short-circuit current, or whether the d.c. component should also be taken into account, and they claim that the former method is in use on the Continent, and the latter both in Great Britain and in America. They agree that it is necessary to test and rate a circuit breaker for making capacity as well as for breaking capacity, and they also agree with the British method of taking into account the d.c. component for expressing the making current. They prefer to neglect it, however, for expressing the breaking current, and they therefore disagree with the British method included in my proposals for that purpose. They also consider that tests made to determine the making current can be carried out irrespective of the test voltage and the number of phases of the circuit. With this I cannot agree, because the stress on making includes something more than the mere mechanical forces set up by the current. There are also thermal effects due to the arc on making contact, the intensity of which is controlled by the voltage; and hence making-capacity tests, like breaking-capacity tests, must be made at the rated voltage. Further, it has been agreed that the duties of a circuit breaker, not only in respect of making and breaking, but also in respect of carrying current, shall not be completely divorced from each other, as the suggestions of Dr. Kopeliowitch and Mr. Brown would entail. The accepted operating-duty cycle (which is intended to represent the use of the circuit breaker in service) definitely combines the effects of the three duties on the general behaviour of the circuit breaker by specifying that they shall be carried out consecutively on the same test circuit, and therefore necessarily all at the same applied or rated voltage, and all with the same number of phases in the circuit.

After a circuit breaker has been closed on a short-circuit, it carries the short-circuit current, and is there-

fore still subjected to heating and electromagnetic effects; and Dr. Kopeliowitch and Mr. Brown agree to include the d.c. component in expressing the making current, because it measures the effects of carrying the current. But a circuit breaker just about to break a short-circuit has also to carry the short-circuit current from its incidence up to the moment of contact separation, and is therefore subjected to similar heating and electromagnetic effects of current-carrying. The obvious conclusion is that since the d.c. component is included to measure the effects of carrying current during making, it is equally logical to include it to measure precisely corresponding effects during breaking. If the breaking current is expressed without taking into account the d.c. component, as Dr. Kopeliowitch and Mr. Brown propose, the same value would have to be given to a symmetrical breaking current as to an asymmetrical breaking current having the same a.c. component; but the asymmetrical current, in service or in a test, would impose a more severe duty on the circuit breaker, both by reason of the additional mechanical forces produced not only before separation of the circuit-breaker contacts but also during the arcing period, and because of the increased rate of generation of gas in the arc bubble during the major half-cycle, although the total amount of gas developed may be approximately the same as that generated by the symmetrical current.

Dr. Kopeliowitch and Mr. Brown wish to omit the d.c. component when calculating the breaking current, because they claim that it assists arc extinction. I agree that arc duration may be shortened, particularly at medium and low voltages, because the effect of asymmetry tends to neutralize the effect of low power factor in promoting the re-establishment of the arc in successive half-cycles; but shortening does not always take place, and if it does not the effect of the d.c. component cannot be relied upon as an easement in compensation of the additional severity imposed by an asymmetrical short-circuit in the other respects referred to above. Judging from the actual behaviour of a large number of oil-immersed 3-phase circuit breakers tested under various conditions of power factor and asymmetry, I have found that whereas the stress is considerably greater at a low power factor than at a high power factor, asymmetrical currents do not in practical behaviour show the easement claimed by Dr. Kopeliowitch and Mr. Brown.

The British standard power factor is 0·1 lagging, which imposes a much more severe condition in respect of arc extinction, and is in consequence a safer standard, than the power factor of 0·3 lagging recommended by Dr. Kopeliowitch and Mr. Brown. Such higher but less severe values can only exist at circuit breakers situated at some distance from the power-supply source, where considerable resistance has been introduced into the circuit by the connecting cables or lines, whereas the intention is that the proposed standard circuit shall correspond in power factor to that of a short-circuit in close proximity to generating plant.

If the d.c. component has a value of 30 per cent of the R.M.S. value of the a.c. component, the R.M.S. resultant of the a.c. and d.c. components is only 4 per cent greater than if the d.c. component is neglected. This means that, in respect of its thermal effect on a circuit breaker, a d.c. component of less than 30 per cent is of no practical importance; but it does produce electro-mechanical forces approximately 1·5 times as great as those produced by the a.c. component only; and there is also a distinct modern tendency towards the use of more nearly instantaneous protective gear and circuit breakers, which operate when the d.c. component is considerably greater than 30 per cent. It is for these reasons that the International Electrotechnical Commission, in Preliminary Recommendation No. 6 for Breaking Current, given in their Publication No. 47, advise that, when the breaking current is calculated from the a.c. component only, "the d.c. component of the breaking current shall not be higher than 30 per cent of the R.M.S. value of the a.c. component," and state that the measurement of the breaking current by the a.c. component only "does not provide for circuit breakers for use under conditions in which there is a larger d.c. component." Contrary to Dr. Kopeliowitch and Mr. Brown, I read Preliminary Recommendation No. 6 as indicating that there is to be further consideration and definition of how the current shall be measured when a larger d.c. component than 30 per cent is present in the breaking current of a fast-acting circuit breaker. Direct-current components undoubtedly exist under modern service conditions with quick-acting circuit breakers, and have definite effects. Hence, since that which exists should not be neglected, my preference is in favour of including the d.c. component in the measurement whenever it is in fact present in the current.

(*g*) *Calculation of Service Short-Circuits and Selection of Circuit Breakers.*—Current measurement has been chosen as the criterion, because it is, of all methods, the one most suitable and convenient for expressing all the quantities that must be represented; that is to say, not only the results of short-circuit tests, but also ratings of circuit breakers assigned from such tests, and values of service short-circuit currents calculated from the actual constants of a network, so that a suitably-rated circuit breaker, with whatever factor of safety may be desired, can easily be selected after a few simple calculations. B.S.S. No. 116–1929 does not specify how circuit-breaker ratings should be selected, and I think that, although I decided when writing the paper not to discuss selection, it would, after all, have been helpful if I had included, in association with the proposals for standardized short-circuit tests, the rules that I have used for many years for calculating service short-circuits and for the selection of ratings, all of which are based upon current values at the given rated voltage. I now put these forward in Appendices V and VI below. It is very helpful to find that Dr. Kopeliowitch and Mr. Brown have also formulated a scheme with a similar aim in view, although it is expressed in different terms, and the point to be settled is whether their method, or the one set out in my proposals, is the more suitable and convenient for its purpose. The essential differences between the two are concerned with the measurement of current and with the way in which voltage is regarded; but, properly used, they should both lead to the selection of circuit breakers having the same physical properties for a given set of actual service conditions, provided that

the same margin of rating over the service short-circuit is allowed.

Let us first consider the problem of selection on the basis of the Appendices, taking as an example the results

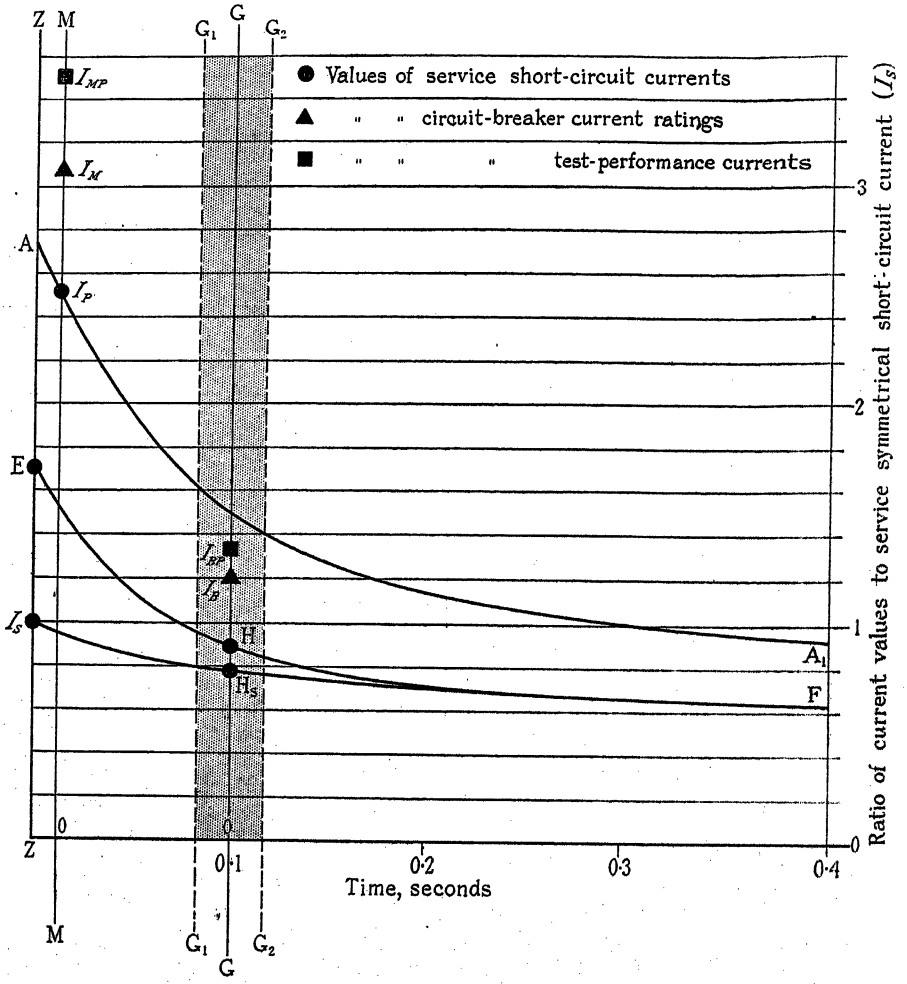


FIG. CC.—Diagram illustrating the relationship between (*a*) performance tests and assigned circuit-breaker ratings, and (*b*) service conditions and selected circuit-breaker ratings in accordance with the proposals of Appendices I, V, and VI.

SERVICE SHORT-CIRCUIT CURRENTS.

A–I_P–A_1 = Typical envelope of peak values of service asymmetrical short-circuit currents, determined from the arithmetical sum of the a.c. and d.c. components.

E–H–F = Typical curve of R.M.S. values of service asymmetrical short-circuit currents, determined from $\sqrt{[(AC/\sqrt{2})^2 + DC^2]}$.

I_S–H_S–F = Typical curve of R.M.S. values of service symmetrical short-circuit currents.

AT INCIDENCE OF SHORT-CIRCUIT (Z–Z).

Z–I_S = Maximum symmetrical alternating current in R.M.S. amperes, i.e. service symmetrical short-circuit current.

AT INSTANT OF MAXIMUM SHORT-CIRCUIT (M–O–M).

O–I_P = Peak value of maximum asymmetrical current, i.e. service asymmetrical short-circuit current, determined from the arithmetical sum of the a.c. and d.c. components.

O–Im = Making-current rating.

O–Imp = Performance making-current.

AT INSTANT OF CONTACT SEPARATION (G–O–G).

G_1G_1–G_2G_2 = Time-zone within which instant of contact separation G–O–G may occur.

O–H_S = R.M.S. value of service symmetrical breaking-current.

O–H = R.M.S. value of service asymmetrical breaking-current, determined from $\sqrt{[(AC/\sqrt{2})^2 + DC^2]}$.

O–Ib = Breaking-current rating in R.M.S. amperes, determined from $\sqrt{[(AC/\sqrt{2})^2 + DC^2]}$.

O–Ibp = Performance breaking-current in R.M.S. amperes, determined from $\sqrt{[(AC/\sqrt{2})^2 + DC^2]}$.

The distance between Z–Z and M–O–M represents the time required after the incidence of the short-circuit for the short-circuit current to reach its first peak value.

of Test No. 572B in relation to the conditions under which the tested circuit breaker (of a British standard rating of 1 000 000 kVA) was to be used. It was connected for its test to generating plant adjusted to be equivalent in short-circuit output (which, as Test No. 419 indicates, was less than the maximum output of the plant), decrement, power factor, and other relevant characteristics, to the plant to which it was subsequently to be connected in service, except that the neutral point was insulated during the test, whereas in service it was to work under the less severe condition of resistance-earthing. This obviously established the suitability of the circuit breaker for its duty in service; but the question arises: In what terms shall its performance and rating be expressed so

that they may be simply compared with its predetermined service requirements? The circuit breaker was selected, on the basis of the proposals in Appendices I, V, and VI, for its ability to make, carry, and break, the specified currents at its rated voltage under the prescribed conditions of severity. The various currents were arrived at in the manner shown below, and Fig. CC has been prepared in order that the relationship between them, in accordance with the proposals, may be more clearly understood.

(A) *Service Conditions (Appendix V).*

(1) The service symmetrical short-circuit current at the incidence of short-circuit (I_s) is

$I_s = 6\,300/(\sqrt{3} \times 0{\cdot}0495)$
= 73 500 R.M.S. amperes [Appendix V (i)].

(2) The service asymmetrical short-circuit current at the incidence of short-circuit (I_p) is

$I_p = 1{\cdot}8 \times \sqrt{2} I_s$
= 187 000 peak amperes [Appendix V (ii)].

(3) The service short-circuit kVA is

$73\,500 \times \sqrt{3} \times 6\,300$
= 800 000 kVA [Appendix V (iii)].

(B) *Ratings of Selected Circuit Breaker (Appendix VI).*

(1) The rated breaking current (I_b) is the current in the 6·6-kV column of Table IV of B.S.S. No. 116–1929 greater than 73 500 amperes (I_s), namely:

I_b = 88 000 R.M.S. amperes [Appendix VI (i)].

(2) The rated making current (I_m) is

$I_m = 1{\cdot}8 \times \sqrt{2} I_b$
= 224 000 peak amperes [Appendix VI (ii)].

(3) The nominal kVA rating is

$88\,000 \times \sqrt{3} \times 6\,600$
= 1 000 000 kVA [Appendix VI (iii)].

(C) *Performance of Selected Circuit Breaker (Tests Nos. 419, 421, 549, and 572B).*

(1) The performance breaking-current (I_{bp}) is:

Average from Test No. 572B (referred to by Dr. Kopeliowitch and Mr. Brown)
97 000 R.M.S. amperes [Appendix I (vi)].

(2) The performance making-current (I_{mp}) is:

Maximum from Test No. 419 (Test No. 572B did not include a "make")
257 000 peak amperes [Appendix I (v)].

(3) The performance kVA is:

From Test No. 572B (referred to by Dr. Kopeliowitch and Mr. Brown)

(*a*) $I_{bp} \times \sqrt{3} \times 6\,600$
= 1 100 000 kVA [Appendix I (ii)].

(*b*) $I_{bp} \times \sqrt{3} \times 6\,300$
= 1 060 000 kVA [at applied test voltage].

The references above, so far as they relate to actual tests, have been to Test No. 572B (except for the "make" test in No. 419), because this test was particularly mentioned and used by Dr. Kopeliowitch and Mr. Brown. An inspection of the other results stated in Test No. 419 will show that the circuit breaker is capable of dealing with considerably higher breaking currents. In accordance with the proposals, all the values given in (A), (B), and (C) above include whatever d.c. component is present. As a matter of interest, if the d.c. component is eliminated from the breaking current (I_{bp}) in (C) (1), the remaining a.c. component is 81 500 R.M.S. amperes, averaged over the three phases; and this is to be compared with the 73 500 R.M.S. amperes (I_s) of the service requirements shown in (A) (1). Further, it may be mentioned that although the power factors recorded in the test figures are all 0·1, they are given as round figures to indicate compliance with the proposed test conditions, the actual values being lower. In Test No. 572B the exact value was 0·07.

If, instead of following the proposals in Appendices I, V, and VI, the calculation of the service conditions, the ratings, and the performances, had been done in accordance with the method advocated by Dr. Kopeliowitch and Mr. Brown, namely, that of using the a.c. component of the breaking current and the recovery voltage, it is obvious that, for the same factor of safety, precisely the same circuit breaker would have been selected, although on paper its rating would have a different value, because—and merely because—of the different units used. The method is not so simple as the previous one, since it is necessary first to ascertain, from general knowledge of the approximate rating to be used, what will be the intervals of time both between the incidence of short-circuit and the instant of contact separation and between the incidence of short-circuit and the instant of final arc extinction, and what will be the decrement of the short-circuit, at the point where the circuit breaker will be used, for the plant and network under consideration; and then to predetermine, from the shorter interval and the decrement, the lower value of short-circuit current at the instant of contact separation, and, from the longer interval and the decrement, the value of recovery voltage at the instant of final arc extinction.

The circuit breaker under discussion was one of a number to be used, according to common British practice, with Merz-Price instantaneous protection on the generators, transformers, and feeders to which they were to be connected. This implies the breaking of a considerable d.c. component in service because of the power factor, which would be of the order of 0·05 lagging; but Dr. Kopeliowitch and Mr. Brown demand that the d.c. component shall not exceed 30 per cent of the R.M.S. value of the a.c. component; and if this is to be complied with it involves deliberate interference with normal operation by the introduction of a 50 per cent increase in time lag. This is an entirely artificial condition; but, even so, if all the values of current and voltage chosen and calculated are in accordance with the circumstances, the result, as has been foreshadowed above, must be the same as that of the simpler method already described. Because of the numerous factors

influencing the resultant shape of the short-circuit decrement, it is very difficult to ascertain the requisite values with accuracy; and this is one of the difficulties of the method, illustrating its unsuitability as a basis for the establishment of standards. The values of service currents, etc., are set out below so as to correspond with those given in the example of the other method, in order to afford a simple means of drawing conclusions.

(1) The service symmetrical short-circuit current at the instant of contact separation is

$$(0{\cdot}8 \times 6\,300)/(\sqrt{3} \times 0{\cdot}0495) = 59\,000 \text{ R.M.S. amperes.}$$

(2) The service asymmetrical short-circuit current at the incidence of short-circuit is [as in (A) (2) of the other method]

187 000 peak amperes.

(3) The service recovery voltage is

$$0{\cdot}8 \times 6\,300 * = 5\,040 \text{ R.M.S. volts.}$$

(4) The service short-circuit kVA is

$$59\,000 \times \sqrt{3} \times 5\,040 = 512\,000 \text{ kVA.}$$

This last value, which is not really kVA, has to be compared with the 800 000 kVA given in the earlier (A) (3); and the relation between the two is simply that 512 000 is $0{\cdot}8 \times 0{\cdot}8 \times 800\,000$. This may appear to be a simple numerical relation; but it is actually one with no physical meaning, because, although 800 000 represents true circuit kVA by virtue of its being a product of simultaneous values of e.m.f. and current, 512 000 is derived from non-simultaneous values. It has already been said that the method of Dr. Kopeliowitch and Mr. Brown is an unsuitable basis for the establishment of standard ratings; and the fact that it depends upon variable multipliers derived from transients, which cannot be accurately known beforehand, is further evidence of this. Even if 512 000 had a physical meaning, instead of being only apparent kVA, all that it would mean would be that Dr. Kopeliowitch and Mr. Brown are using a measuring rod graduated in units 1·56 times the size of mine; and such a difference cannot change physical facts. From the comparison I have made between the two methods, I think it will be apparent that the one based on the proposals in the Appendices is as logical as that of Dr. Kopeliowitch and Mr. Brown, and is more convenient than theirs in selecting a circuit breaker for a given duty. In addition, it has the merit of being simpler.

The method of Dr. Kopeliowitch and Mr. Brown is based upon varying time intervals and decrement characteristics, and hence it is difficult to conceive how it can specify any definite ratio of the making current to the breaking current. Evidence for this is contained in the variety of ratios quoted by them. On the other hand, as Fig. CC shows, Appendix VI, taken in conjunction with Appendices I and V, ensures that the circuit breaker selected has an adequate making capacity, quite irrespective of any time intervals or decrement characteristics, because there is a definite ratio between the specified values of the making current and the breaking current, sufficiently high to correspond to the lowest power factor likely to occur at any time. The great advantage of this anchoring of values of the making currents and the breaking currents for any particular case is that a circuit breaker adequate for its duty can be selected as a result of an arithmetical calculation of the simplest possible kind, in the same terms as are commercially used to describe electrical plant of all kinds. All that is necessary to arrive at the minimum standard kVA rating of the circuit breaker required is to multiply the service short-circuit kVA by 100 and to divide the product by the total percentage reactance of the plant and network up to the point at which the circuit breaker is to be installed. That is to say, 10 000 kVA of generating plant with 10 per cent reactance requires 100 000-kVA circuit breakers.

Footnote to Appendices V and VI (see Page 661).

Note.—Like the earlier Appendix I, these new Appendices are intended to give guidance on a convenient standard basis. It is obvious that at any particular position on the system under consideration the conditions may be modified by easements or aggravations of various kinds; and selection may have to be correspondingly modified in the direction of choosing a smaller or a larger standard rating than would have been chosen for the standard conditions.

Possible Easements.—When we have ascertained a standard of performance on the lines proposed in the paper, and have assigned definite standard ratings, it will be possible to compare conditions of service with those of the standard test circuits; and some of the conditions that may allow smaller ratings to be selected are given here as suggestions:—

(*a*) Certain positions on the network may have a higher power factor than that of the standard test-circuit.

(*b*) Certain positions close to plant may have a lower recovery voltage than that of the standard test-circuit.

(*c*) Longer time-lag may have the effect of lowering the required short-circuit breaking-current, and in some instances (for example, at the higher voltages) it may be possible to deal with the consequent higher ratio of the making current to the breaking current.

(*d*) Easement of circuit-breaking stress may be given by decrease of rate of rise of restriking voltage, occasioned, for example, by the fact that the capacitance of the network is greater than that of the standard test-circuit.

(*e*) Factor of safety may be reduced in places or under conditions where this is justified.

(*f*) The operating duty may be varied so as to afford an easement; for example, if making the short-circuit is eliminated in practice.

(*g*) The conditions of earthing may be varied in practice.

Possible Aggravations.—On the other hand, the conditions may be such that larger ratings have to be selected because of aggravations of severity; for example, the opposites of those set out in (*a*) to (*f*) above would have this effect.

* Strictly, 0·8 should be something less in (3) if it is correct in (1); but the approximate value is used for convenience, because the difference is small.

APPENDIX V.*

PROPOSALS FOR STANDARDIZED CALCULATION OF SERVICE SHORT-CIRCUITS.

Item	Specification	Interpretation
(i) Calculation of service symmetrical short-circuit current	The maximum symmetrical alternating current at the incidence of short-circuit expressed in R.M.S. amperes (I_s) and calculated from: (*a*) $I_s = V/$(Phase factor $\times Z$), where V = rated voltage, and Z = total impedance, up to the fault, of the circuit connected through the circuit breaker. (*b*) $I_s =$ (kVA rating of aggregate generating plant $\times$ 100) $\div$ (percentage reactance up to the fault $\times$ phase factor $\times$ rated voltage)	The fault shall be assumed to occur at the point that gives the maximum short-circuit current through the circuit breaker and shall be determined on the basis of the aggregate plant likely to be connected at any time
(ii) Calculation of service asymmetrical short-circuit current	The maximum asymmetrical current after the incidence of short-circuit, expressed in peak amperes (I_p) and calculated from $I_p = 1{\cdot}8 \times \sqrt{2} I_s$	The factor of 1·8 is chosen to represent a practical value of what is commonly known as the "doubling" effect
(iii) Calculation of service short-circuit kVA	$I_s \times$ phase factor $\times$ rated voltage	A term of convenience that enables the short-circuit to be expressed on the lines of Clause 46 of B.S.S. No. 116–1929 in the same terms as the ratings of generators, transformers, and circuit breakers, so that they may be directly compared with each other

APPENDIX VI.*

PROPOSALS FOR STANDARDIZED SELECTION OF CIRCUIT-BREAKER RATINGS.

Item	Specification	Interpretation
(i) Selection of a breaking-current rating	A standard current-rating (I_b), chosen from Table IV of B.S.S. No. 116–1929, not less than the service symmetrical short-circuit current (I_s) provided that the time interval between the incidence of short-circuit and contact separation is of the order of 0·1 sec.	The specification is arbitrary, but is conveniently practical, because the short-circuit characteristics of average generating plant are such that, if the time interval between the incidence of short-circuit and contact separation is of the order of 0·1 sec., an asymmetrical short-circuit has usually become, during that interval, approximately equal to or less than the service symmetrical short-circuit current at the incidence of short-circuit
(ii) Selection of a making-current rating	A rating (I_m) not less than the service asymmetrical short-circuit current (I_p) and calculated from $I_m = 1{\cdot}8 \times \sqrt{2} I_b$	It is obvious that the specification applies universally, since it is impossible to avoid "making" the service asymmetrical short-circuit current
(iii) Selection of a nominal kVA rating	The standard kVA rating, chosen from Tables III and IV of B.S.S. No. 116–1929, corresponding to the breaking-current rating (I_b) at the rated voltage and with the appropriate phase factor, and therefore not less than the service short-circuit kVA	A rating of convenience that enables the size of a circuit breaker to be described in the same terms as the sizes of generators and transformers, so that they may be directly compared with each other

* See "Footnote to Appendices V and VI" on page 660.

APPENDIX VII.

METHOD OF OBTAINING THE POWER FACTOR OF AN ASYMMETRICAL PHASE OF A SHORT-CIRCUIT FROM AN OSCILLOGRAPH RECORD.

The method is based on the fact that the d.c. component of a short-circuit current in a series test-circuit has the general form:—

$$I_d = I_{d0}e^{-Rt/L}$$

where I_d is the value of the d.c. component at any instant t, measured in seconds from the incidence of the short-circuit; I_{d0} is the value of the d.c. component at the incidence of the short-circuit; L is the effective inductance of the whole circuit, in henries; R is the effective resistance of the whole circuit, in ohms; L/R is the time-constant of the whole circuit, in seconds; and e is the base of Napierian logarithms.

The procedure for arriving at the value of the power factor is as follows:

(1) First determine L/R by drawing in, on an asymmetrical short-circuit wave, the curve of the d.c. component, and obtaining from it the time-constant L/R by any of the usual methods. Two of these methods are referred to here as examples, namely:

(*a*) Determine the ratio I_d/I_{d0} for any point t, and read off, from a published table* of values of e^{-x}, the value of x that makes e^{-x} equal to this ratio. This value of x is equal to Rt/L, and so the time-constant L/R in seconds is given by dividing t by x.

* Such tables are contained in many books of physical and mathematical constants.

(*b*) Determine the value of t at which I_d has fallen to 36·8 per cent of I_{d0}. This time t is equal to the time-constant L/R.

Note.—In view of the fact that the curve of the d.c. component is drawn in by hand, and not recorded directly as a physical quantity, it is desirable to take the mean of several readings adjacent to the selected point t, in order to eliminate any small errors. Hence method (*a*) is preferable on the score of accuracy to method (*b*), which does not allow this to be done.

(2) From L/R, as found in (1) above, calculate X/R from

$$X/R = \omega L/R$$

where $\omega = 2\pi \times$ the frequency of the circuit at the instant t.

(3) From X/R, as found in (2) above, calculate the power factor of the asymmetrical phase from

$$\cos\phi = \cos \text{ arc } \tan(X/R)$$

When one phase of a 3 phase short-circuit is symmetrical, the other two phases have equal degrees of asymmetry, and the power factor of each of these two phases may be taken, with a reasonable degree of accuracy, as the power factor of the polyphase test circuit. In all other cases the 3 phase short-circuit has asymmetry of varying degree in all the three phases. It is thus possible, for the great majority of short-circuits, to obtain the value of ϕ $[= \text{arc } \tan(X/R)]$ for each of the three phases, and so, by taking the cosine of the average of the three angles, to arrive at the value of the power factor of the polyphase test circuit, as defined in Proposal (viii) (*b*) of Appendix I.

SYMMETRICAL COMPONENTS, AND THEIR APPLICATION TO THE PHASE CONVERTOR.*

By Professor F. M. DENTON.

(*Paper received 30th November, 1931.*)

SUMMARY.

The object of the paper is to explain in common-sense terms the method of calculation developed in 1918 by Mr. C. Le Geyt Fortescue and generally known as the method of symmetrical components.

This method shortens and simplifies the solution of problems of unbalanced polyphase systems. It has made practicable the calculating board by which such problems may be solved automatically.

In order to demonstrate its wide usefulness, the method of symmetrical components is here used in an explanation of the action of the phase convertor.

INTRODUCTION.

Problems of polyphase systems may be solved as simply as those of single-phase systems, provided the systems are balanced. Unbalanced systems, on the other hand, present problems whose solution by the ordinary methods demands a long and tedious application of complex numbers and determinants. In small systems such problems are seldom important, but in large systems they are of great importance, as a heavy short-circuit on one phase may disturb every part of a large system. To predict such disturbances is not easy; yet it is essential to prepare for them and to limit their possible magnitude.

In 1918 Mr. C. Le Geyt Fortescue read before the American Institute of Electrical Engineers† a paper entitled "Symmetrical Components," describing his simple and complete method of attacking the problem of unbalanced polyphase systems. A discussion of that method, with actual examples, was given in 1928 by C. F. Wagner and R. D. Evans in the *Electric Journal*.‡ The present paper is intended as an introduction to the Fortescue method.

In order to show its general usefulness the method is applied in an explanation of the phase convertor, a machine the discussion of which in textbooks seems to have been neglected.

In order to evolve the method of symmetrical components by common-sense reasoning, it is necessary to recall the following familiar conceptions of electrical theory.

THE ROTATING MAGNETIC FIELD.

Nikola Tesla's invention of the induction motor brought into prominence the rotating magnetic field.

The stator of a 2-pole 2-phase induction motor has two mutually-perpendicular windings, A and B, as indicated in Fig. 1(*a*). The currents in A and B are represented vectorially by I_a and I_b in Fig. 1(*b*). The resultant m.m.f. and flux due to I_a and I_b are constant. The flux produced is diametrical (bi-polar) and rotates synchronously. Whether the flux rotates clockwise or

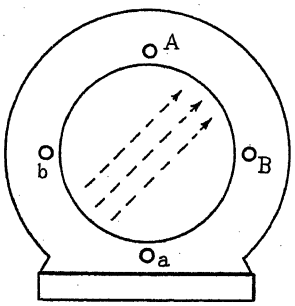


FIG. 1(*a*).

counter-clockwise depends on whether I_a leads or lags relatively to I_b.

This simple case is easily understood by the ordinary vector method. A picture still more clear can be had by using the notion, attributed to Ferraris, that any sinusoidal single-phase field with its axis fixed in space may be thought of as the resultant of two equal d.c. fields of constant strength rotating synchronously in

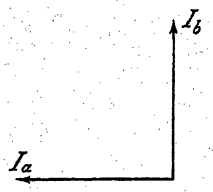


FIG. 1(*b*).

opposite directions. Thus the vertical a.c. field of Fig. 2(*a*) may be imitated precisely by a pair of bar magnets [Fig. 2(*b*)] rotating in opposite directions about the fixed centre O.

The stator of Fig. 1 may be replaced, in principle, by two such coils as that of Fig. 2(*a*) set mutually perpendicular, as in Fig. 3(*a*). Both coils are fixed in space, A producing a horizontal and B a vertical a.c. field. If the alternating currents in A and B were in phase we should have Fig. 3(*a*) equivalent to Fig. 3(*b*), and this would represent not a rotating resultant field but a single-phase a.c. field inclined along OP.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Transactions of the American I.E.E.*, 1918, vol. 37, p. 1027.

‡ *Electric Journal*, 1928, vol. 25, p. 151.

Of course, in the 2-phase motor I_a and I_b are in quadrature, so that at the moment when the magnets equivalent to coil A are as in Fig. 3(*c*) those equivalent to B are as in Fig. 3(*d*). Superimposing these two pairs

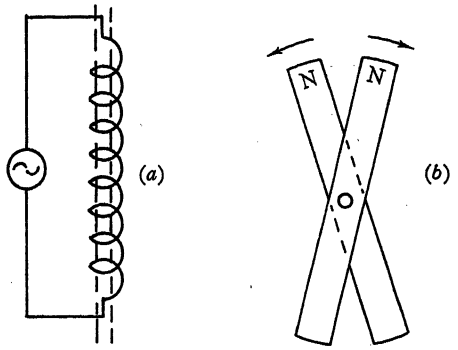


FIG. 2.

of magnets gives Fig. 4. The fields of two of the magnets in this group cancel each other, and those of the remaining two assist. The two that cancel rotate together and continue to cancel each other; the two that assist rotate

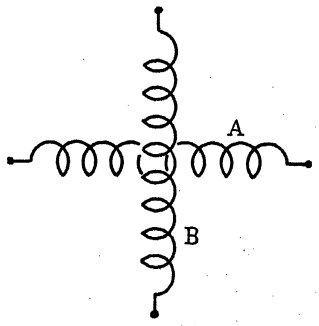


FIG. 3(*a*).

together and continue to assist, forming a synchronously-rotating field of constant strength equal to the maximum instantaneous strength of either single-phase coil A or B acting alone.

The rotation is counter-clockwise. Had the phase

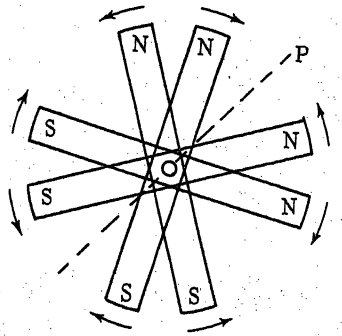


FIG. 3(*b*).

order of I_a and I_b been reversed the rotation would have been clockwise. In common-sense considerations of polyphase systems this method of Ferraris is helpful and very simple.

The case just examined seems like a perversion of simplicity, for we have taken a simple rotating field and analysed it into four superimposed rotating fields. It is given in order to illustrate the point that the number of rotating fields into which one rotating field may be

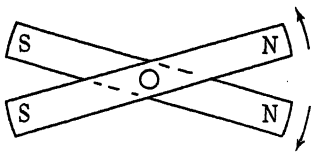


FIG. 3(*c*).

analysed is arbitrary. If desired, the diametrical rotating field may be analysed, for instance, into 24 superimposed rotating fields. For, as is well known, the diametrical rotating field of Fig. 1 may also be obtained by using, say, a ring winding tapped at 4 points

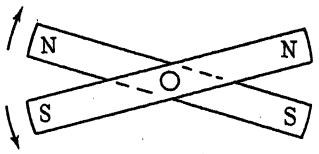


FIG. 3(*d*).

and supplied with 2-phase current, or tapped at 24 points and supplied with 12-phase current. The vector diagram of current for this case is shown in Fig. 5. The effects of each of the 12 currents OA, OB, etc., can

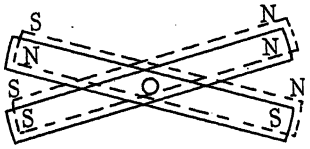


FIG. 4.

be imitated by a pair of bar magnets rotating oppositely. In all there will be 24 bar magnets, certain pairs of which will cancel, while others will mutually assist, the net result being one single diametrical (bi-polar) flux rotating synchronously.

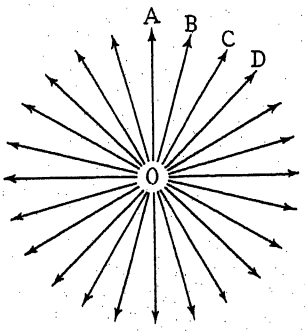


FIG. 5.

In the theory of symmetrical components it is usual to speak of such component rotating magnets, m.m.f.'s, current groups, or voltage groups, as of "positive sequence" or "negative sequence," according as they rotate clockwise or counter-clockwise.

THREE-PHASE SYSTEM REGARDED AS TWO-PHASE.

Where the open-delta connection is adopted, if one unit in a delta-connected 3-phase bank of transformers burns out it may be removed, and the remaining two transformers of the delta bank can maintain the proper 3-phase line voltage and continue to carry a considerable

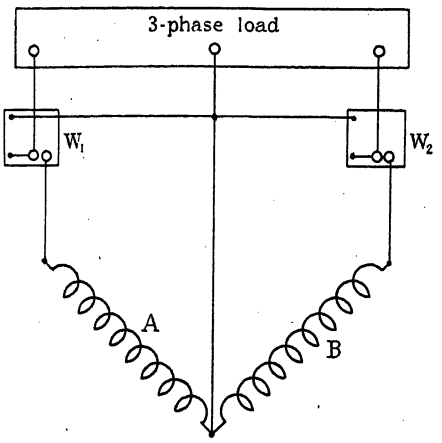


FIG. 6.

3-phase load. Similarly, if one phase of the winding of a 3-phase delta-connected generator should burn out the machine may continue to run on open delta.

Now an open-delta winding has only two phases, the phase difference between the windings being 120°, instead of the 90° used in what are commonly known as 2-phase systems. This fact makes unnecessary any special proof of the legitimacy of the well-known 2-wattmeter method (see Fig. 6) of measuring a 3-phase load (balanced or unbalanced). From an inspection of the figure it is obvious that W_1 measures the output of phase A and W_2 that of phase B. The input to the load is the output of the generator and so must equal $(W_1 + W_2)$, due respect being paid to the fact that on low power factor one wattmeter may read backward.

PHASE-SEQUENCE INDICATOR FOR 2-PHASE SYSTEM.

A well-known method for finding the phase sequence of a 2-phase system is to use the simple star network of

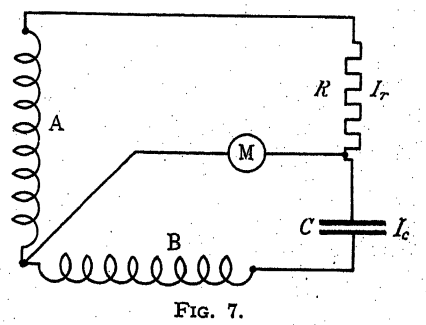


FIG. 7.

Fig. 7. If the direction of rotation of the generator is such (we will call it clockwise) that phase A attains maximum instantaneous positive voltage earlier in time than B, the vector diagram is as in Fig. 8(*a*). Reversing the direction of rotation gives Fig. 8(*b*). The usual counter-clockwise rotation of vectors is retained in all the diagrams, without regard to the direction of rotation of the generator. The current in the ammeter M of the phase-sequence indicator is the difference between the current I_r in phase with V_a (R being an ohmic resistance) and the current I_c (C being a condenser of R ohms reactance) leading V_b by 90°, as in Fig. 8(*c*). Thus the ammeter takes zero current.

Reversing the direction of rotation of the 2-phase

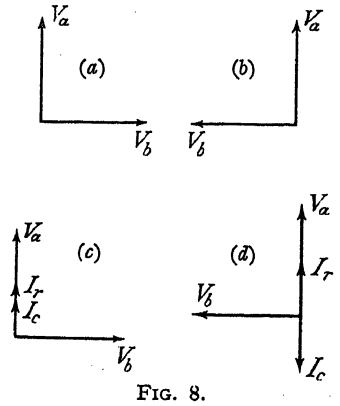


FIG. 8.

generator gives the diagram shown in Fig. 8(*d*), the ammeter current then being the vector difference of I_r and I_c. The ammeter reading is twice as great as it would be if the ammeter in series with R were joined like a voltmeter across one phase of the generator.

PHASE-SEQUENCE INDICATOR FOR 3-PHASE SYSTEM.

The 2-phase indicator just described may be made suitable for a 3-phase system by joining the ammeter at a properly-chosen point along R instead of at the junction of R and C. This is shown in Fig. 9, in which

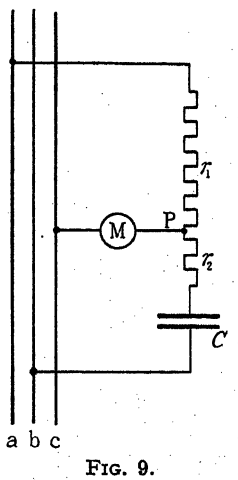


FIG. 9.

r_1 and r_2 are two sections of the ohmic resistance R. The point P must be so chosen that

$$r_1 = \sqrt{\left(r_2^2 + \frac{1}{C^2\omega^2}\right)}$$

and

$$\frac{1}{(r_2 C\omega)} = \tan 60° = 1{\cdot}732$$

We then have the diagram of Fig. 10. The ammeter takes the vector difference of a current I_{r_1} in phase with the voltage between lines "a" and "c," and a current I_x leading the voltage between lines "c" and "b" by the angle

$$\text{arc tan}\left(\frac{X}{r_2}\right) = \text{arc tan}\left(\frac{1}{r_2 C\omega}\right)$$

where $\omega = 2\pi \times$ frequency.

To fix ideas let us imagine the 2-pole 3-phase generator

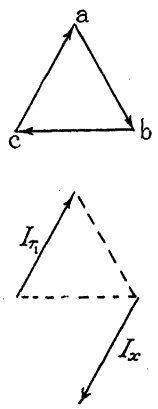


FIG. 10.

connected as in Fig. 11, producing, for clockwise rotation, what we will call "clockwise" or "positive" phase-sequence. The N pole sweeps across the phases of the winding in the order A, B, C, so that the e.m.f. in phase A leads that in phase B, and B leads on C. We thus have, for clockwise rotation, the vector diagram of Fig. 10; and for counter-clockwise rotation that of Fig. 12.

For clockwise rotation the ammeter reads the vector difference (Fig. 10) of I_{r_1} and I_x, the magnitude of which

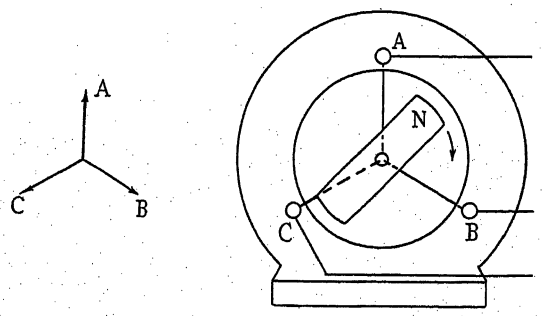


FIG. 11.

is $2I_{r_1}$, i.e. $2I_x$. With the field rotation reversed, the vector diagram is as in Fig. 12. The N pole sweeps across the windings in the order A, C, B, so that the voltage vector OA leads on OC, and OC leads on OB. The current I_x leads by 60° the voltage BC which sends it. The ammeter reads the vector difference of I_x and I_{r_1}, which is equal in magnitude to I_x or I_{r_1}. Thus reversal of rotation has halved the reading of the ammeter. With this form of star network we have to choose between two readings, one twice as great as the other, the higher reading indicating what may be called "positive phase-sequence," while the lower one indicates negative sequence.

The introduction of transformers makes it possible to have a zero reading instead of a "higher" reading. The phase-sequence indicator, with its ammeter, is shown on the right in Fig. 13. Its action, which is the same whether the line be joined directly to A, B, C, or at the terminals a, b, c, of the transformers, depends upon the fact that the ammeter takes twice (say $2I$ amperes) as much current for positive sequence as for negative. If, however, the secondary connections of one of the transformers be reversed, the reading will be zero for positive sequence and $1{\cdot}732I$ for negative. The reversal of one secondary has caused the ammeter

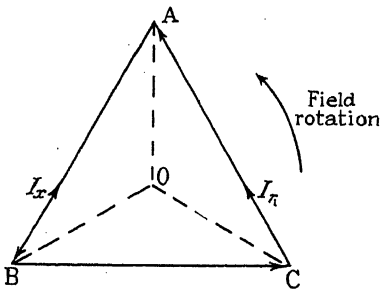


FIG. 12.

to read, for either sequence, the vector sum of I_{r_1} and I_x, instead of the vector difference. Should it be desirable to make the instrument read zero for negative instead of positive sequence, it is necessary only to interchange two of the leads A, B, C.

When no transformers are used the reading of the sequence indicator is proportional to the line voltage. If, for instance, for the sequence of Fig. 10 the ammeter reads $1{\cdot}3$ amperes, the value of r_1 being, say, 125 ohms, then the line voltage must be given by

$$V = \frac{(1{\cdot}3 \times 125)}{2}$$

We assume the impedance of the ammeter to be negligible compared with 125 ohms, and remember that only half the current (i.e. half of $1{\cdot}3$ amperes) flows in r_1.

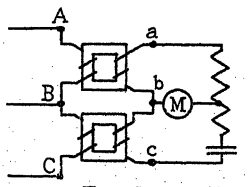


FIG. 13.

SUPERPOSITION OF TWO 3-PHASE CURRENT SYSTEMS HAVING OPPOSITE PHASE-SEQUENCES.

Two 3-phase generators rotating synchronously in opposite directions with their windings joined in series would give a 3-phase line voltage containing a positive and a negative phase-sequence. Such a system would send into a load two sets of currents, namely a positive-sequence set and a negative-sequence set. If a pair of

phase-sequence indicators were connected across the line, one with its terminals joined a to A, b to B, and c to C (a, b, c, being the terminals of the indicators), while the terminals of the other were joined, say, a to A, b to C, and c to B, they would give readings proportional respectively to the e.m.f.'s produced by the two generators.

The case of two similar, equally-excited generators coupled together and having opposite rotations and therefore opposite phase-sequences, is interesting. For if we look endwise along the shafts we see a picture such as Fig. 14(*a*), in which what now appears as one single

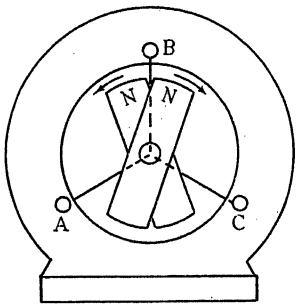


FIG. 14(*a*).

winding constituted by the two stator windings, is acted on by two oppositely-rotating fluxes. These two fluxes are equivalent to one vertical a.c. flux, and the system is thus a single-phase system. Across AC we have an a.c. voltage, and B is a point midway in potential between A and C. Diagrammatically the connections are as in Fig. 14(*b*) for the positive-sequence indicator, and as in Fig. 14(*a*) with A and C interchanged for the negative-sequence indicator. The two indicators give equal readings.

This extreme case in which our so-called 3-phase system contains negative-sequence currents actually

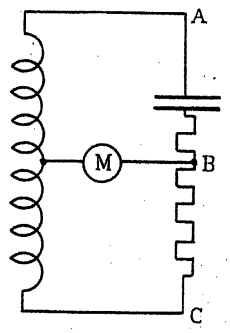


FIG. 14(*b*).

equal to the normal positive-sequence currents, is one of maximum possible unbalance. Unbalance on a 3-phase system is produced when a single-phase load is taken in addition to a balanced 3-phase load. The case of extreme unbalance occurs when the 3-phase load is zero and the whole load is single-phase.

Less serious unbalance is caused when the load is equivalent to a large positive-sequence current added to a small negative-sequence current. For instance, the unbalanced 3-phase set of currents shown by the unsymmetrical delta of Fig. 15(*c*) may be analysed into the large positive-sequence component of Fig. 15(*a*) and the smaller negative-sequence component of Fig. 15(*b*). If Fig. 15(*c*) represented an unbalanced system of voltages it might be analysed into its components by means of two phase-sequence indicators. This analysis, though useful, would be incomplete. It would give the magnitudes but not the phase relationship of the component systems shown in Figs. 15(*a*) and 15(*b*). The question of phase relationship will be dealt with later by two methods, one graphical and the other mathematical.

In order to use phase-sequence indicators for the analysis of systems of currents we must introduce shunts or series transformers, as in Fig. 15(*d*). This

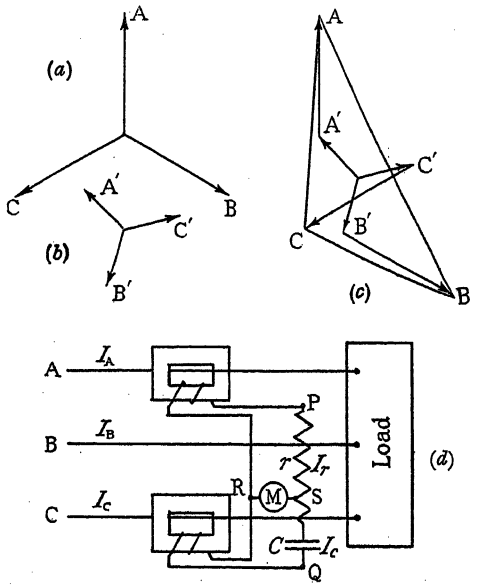


FIG. 15.

simple arrangement has, however, the disadvantage that it is affected by zero-sequence currents, the system of Fig. 15(*d*) acting in respect of such currents exactly as that of Fig. 14(*a*) does towards single-phase current. In practice, therefore, the analysis of an unbalanced system of 3-phase currents demands a network having a transformer in each of the three lines.*

THE ZERO-SEQUENCE COMPONENT.

The statement made in reference to Fig. 4, that any polyphase system of currents may be analysed into rotating systems, is true and general, but it refers only to true polyphase systems. A true 3-phase system of currents must require three wires and no more. A 4-wire 3-phase system is not true 3-phase; it is rather to

* If desired, the ammeter M in Fig. 15(*d*) may be replaced by a short-circuit, and the voltage across PQ may be measured instead of the current at A. The current I_r is proportional to and in phase with the current in line "*a*," while I_c is proportional to and in phase with the current in line "*b*." The voltage across PS is then in phase with I_A, and the voltage across SQ lags by 60° on I_B. Then if the 3-phase load should happen to be balanced (I_A 120° out of phase with I_B), the voltmeter across PQ would give a high reading for one phase sequence and zero reading for the reversed sequence.

be regarded as three single-phase systems with a common return conductor.

It is possible to superimpose a single-phase current upon a 3-wire 3-phase system of currents in such a way that no resultant m.m.f. and no resultant flux is produced in the 3-phase machines on the system. Such a case is shown in Fig. 16, in which the earth current due to the e.m.f. injected at E divides equally between the three line wires, producing no resultant diametrical or inter-polar flux in either generators or motors. Such a superimposed single-phase current is called by Fortescue a voltage to earth it is called a zero-phase-sequence voltage. A voltmeter between neutral and earth measures the zero-phase-sequence voltage.

The effect of the zero-sequence current is seen by reference to three current transformers with their secondaries in delta, as shown in Fig. 17. In addition to the 3-phase currents, probably unbalanced, in A, B, and C, there are the three equal components (all in phase with one another) of the earth current. These produce three equal in-phase voltages in the delta-connected secondary system, and set up a current

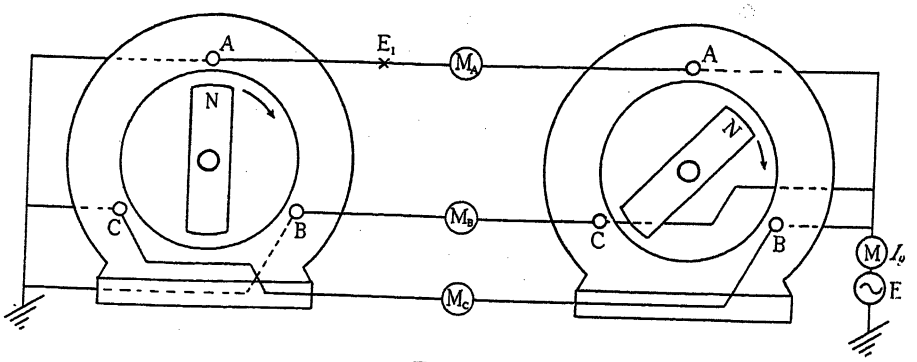


FIG. 16.

a " zero-phase-sequence " current. It neither produces any rotating fields nor can its effect be analysed into that of pairs of oppositely-rotating fields. It is in this sense non-inductive with respect to generators and motors.

Any neutral current (and this means, usually, earth current) is of zero phase-sequence. It need not, and usually does not, originate from such an external e.m.f. as that shown at E in Fig. 16; it is usually caused by some e.m.f. within the polyphase system. However, even if the e.m.f. causing the earth current were at E_1, say, we should still consider that the earth current I_g

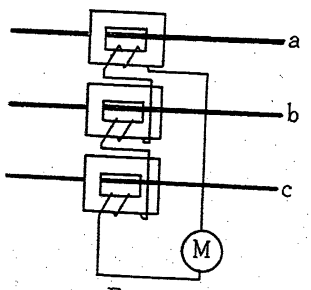


FIG. 17.

(indicated by ammeter M) was divided equally between the lines A, B, and C. The ammeters M_A, M_B, and M_C, would each be said to carry the vector sum of its own line current and one-third of I_g. The 3-phase system of currents left after subtracting, vectorially, one-third of I_g from each, would be the system which our phase-sequence indicators would then analyse into two balanced 3-phase sets of opposite sequence.

Thus the phase-sequence indicators are not affected by the earth current, and we therefore call that current the zero-phase-sequence current. Similarly if there is circulating round the delta. This is the zero-sequence current, and it may be measured by an ammeter in the delta (as in Fig. 17) or by an ammeter connected by series transformers (as in Fig. 18). In Fig. 18 currents of all sequences flow in the secondaries of the three transformers, but the ammeter responds only to zero-sequence currents. The zero-sequence currents are in phase with one another through the ammeter; the 3-phase currents cancel.

Graphical analysis.—The positive, negative, and zero phase-sequence components into which a pair of phase-sequence indicators analyses a system ought to be

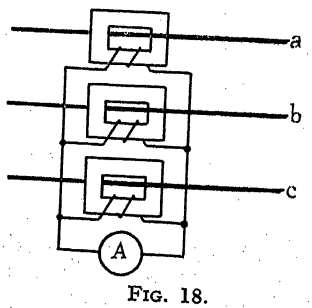


FIG. 18.

supplemented by a knowledge of the phase relations of the components. Without that knowledge Figs. 15(*a*) and 15(*b*) cannot be properly combined. Fig. 15(*c*) was an arrangement chosen at random.

The phase relation of the components may be found by a graphical method. Let the line voltages of an unbalanced 3-phase system be represented as in Fig. 19. To find the positive-sequence component, the vector OC must be turned clockwise about O through 120° to the position OC′. Then the vector OB is turned counter-clockwise through 120° to the position B′.

The vectors OA, OB′, and OC′, are now strung together in series as in Fig. 20, and the resultant OC′ divided by 3 gives the radius of the positive-sequence component.

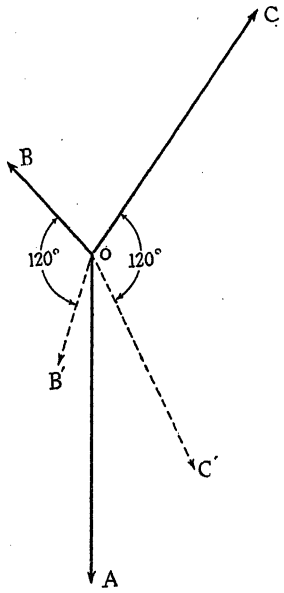


FIG. 19.

To find the negative-sequence component the above procedure is repeated, except that the words "clockwise" and "counter-clockwise" must be interchanged.

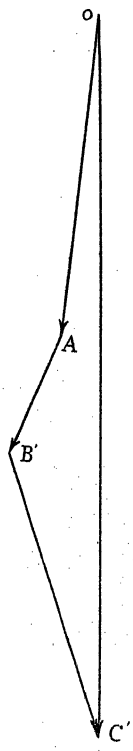


FIG. 20.

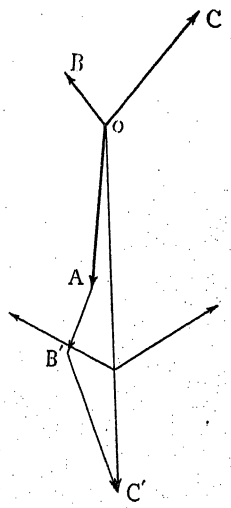


FIG. 21.

The two stages of the procedure indicated in Figs. 19 and 20 are shown in Fig. 21. The radius of the positive-sequence component is one-third of OC′, and its direction in relation to OA is as shown. The procedure for finding

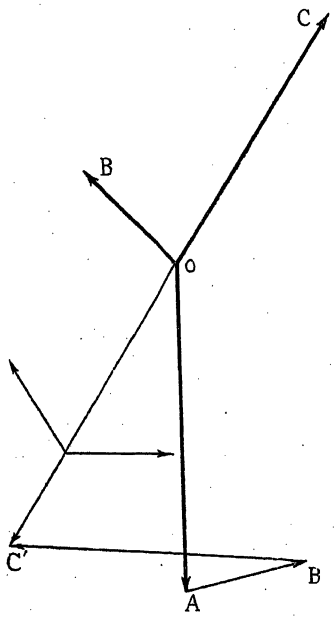


FIG. 22.

the negative-sequence component may be followed by reference to Fig. 22.

The zero-sequence component is got by stringing together in series the given vectors OA, OB, and OC, as in Fig. 23, the value of the resultant OC being 3 times that of the zero-sequence component, properly related in phase to OA.

Mathematical analysis.—Before giving the theoretical justification for the graphical procedure outlined above, we may briefly consider the symbolic method of performing the same operation.

The graphical process of turning certain lines through 120° may be carried out symbolically by means of "operators." The most familiar of all operators is (− 1). When (− 1) operates on a vector of any magnitude pointing due north, it turns it into a vector of the same magnitude pointing due south. The operator

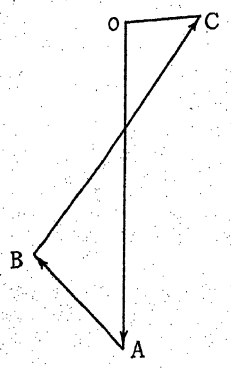


FIG. 23.

(− 3), in addition to turning a vector through 180°, multiplies its magnitude by 3.

The well-known operator "j" turns a vector counter-clockwise through 90°. When j acts twice in succession it turns the vector twice through 90°, i.e. through 180°.

Thus $$j \times j = -1$$

and $$j = \sqrt{(-1)}$$

An operator containing numerals, + and − signs, and the symbol j, can be so chosen as to change the magnitude and direction of a vector in any desired way. Thus the operator which turns a vector through 120° counter-clockwise is $(-0{\cdot}5 + 0{\cdot}866j)$. Fortescue uses the symbol "a" for this operator. If the operator a acts twice in succession upon the same vector it turns it counter-clockwise through 240°, which is the same as turning it clockwise through 120°. The operators a and a^2 are used in finding symmetrical components. For instance, a balanced star system of three equal voltages V, would be represented symbolically by V, a^2V, and aV. Balanced 3-phase star or delta systems are easily dealt with, and it is convenient to have one brief symbol in place of V, a^2V, aV. Fortescue uses the symbol S^1V. S^1 is thus an operator which turns one single-phase quantity into a balanced 3-phase system of positive sequence. Whether this be thought of as a star or a delta system is a matter of convenience.

The operator S^1 produces a 3-phase set having clockwise sequence. This is because it means: multiply first by 1, then by a^2, and finally by a. It is called the "positive-sequence operator." Negative sequence is produced by the operator $(1, a, a^2)$, the symbol for which is S^2.

To complete the system of operators, there is the zero-sequence operator which, acting on a vector, produces not a star or delta, but a set of three superimposed vectors equal to the vector operated on.

Proof of graphical analysis.—The legitimacy of the graphical method may be proved by inspection. If the analysis is correct, then the components may be used to build up the given unbalanced system. This building-up is illustrated in Fig. 24, where for clearness the zero-sequence component is shown three times its proper length. The equivalence of the three sequence-sets (positive, negative, and zero) to the unbalanced system is seen by applying the rotations to these instead of to the unbalanced limbs. Thus the 120° clockwise turning is applied to OC′ and OC″, and to one of the three superimposed zero-sequence vectors of Fig. 24, instead of to OC. This brings OC′ to OA′ and OC″ to OB″, while it displaces one zero-sequence vector through 120° forward. The counter-clockwise turning is applied to OB′ and OB″, and to one of the zero-sequence vectors, instead of to OB. This brings OB′ to OA′, and OB″ to OC″, whilst displacing a zero-sequence vector 120° backward.

The first turning operation causes all three limbs of the positive-sequence set to be superimposed, while it merely changes the sequence of the negative set. Its effect upon the zero-sequence set is to turn it into a star. The stringing process adds superimposed elements arithmetically, while it cancels stars by turning them into deltas whose beginnings and ends coincide. Thus the first stringing process gives the arithmetic sum of the three positive-sequence limbs, properly oriented, whilst it cancels the negative- and zero-sequence sets. Similarly the second operation gives the negative-sequence set.

The third operation is to string together the original given vectors without any turning. If this produced

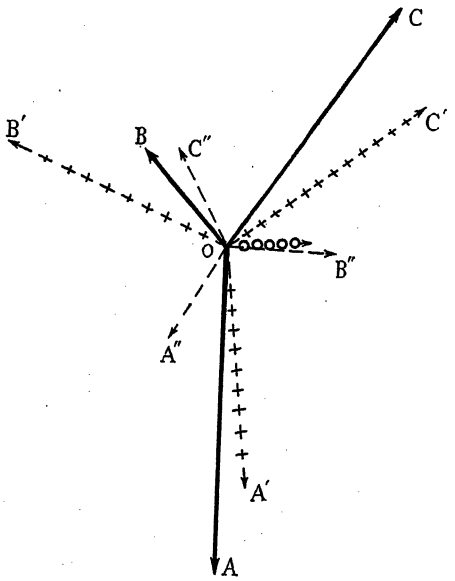


FIG. 24.

Original unbalanced currents.
++ Positive-sequence components.
−− Negative-sequence components.
o o o Zero-sequence components.

a closed delta there could be no neutral- or zero-sequence component. The vector needed to close the delta figure is the arithmetical and vector sum of the three equal elements of the zero-sequence component.

APPLICATION OF METHOD OF SYMMETRICAL COMPONENTS.

Fortescue replaces an unbalanced system of three currents by three balanced systems. Why is it a simplification thus to replace three currents by nine?

The point is that the three original currents are interdependent; to change any one of them is to change also the other two. Fortescue's three 3-phase systems

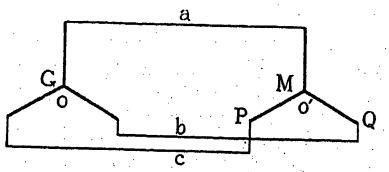


FIG. 25.

are balanced, and therefore mutually independent. They differ in phase sequence, and this is taken care of by the use of simple operators. They differ in phase, and this is taken care of by the ordinary vector method used for single-phase systems.

Before considering complicated cases it is well to master the procedure in a simple case. We take, for instance, Fig. 25, in which a star-connected generator

G supplies current to a star-connected synchronous motor. The only current in this system is of positive sequence. The three phases behave alike, and for purposes of calculation we may replace the 3-phase system by any one of its three phases. In doing so, however, we must remember that Fig. 25 omits the return conductor of each of its star-connected phases. To complete Fig. 25 we imagine the three neutral leads to have been introduced. When these three leads have been combined into one conductor they need have no cross-section and so may be removed, because the vector sum of the neutral currents is zero. Not only do the currents cancel, but so also do the voltage-drops along the neutrals. Thus in analysing the system into single-phase components we must give to each component a return lead of zero impedance. This lead may be called a " busbar of zero potential."

The single-phase system by which, for purposes of calculation, we replace Fig. 25, is that of Fig. 26. Here the single-phase generator is simply one limb of the star-connected generator of Fig. 25, E_g being its e.m.f. and Z_g its internal impedance. The latter is usually called the synchronous impedance; it is the same thing as the positive phase-sequence impedance. The single-phase load is one limb of the motor of Fig. 25, the upper conductor is one of the 3-phase lines, and the dotted line is a lead of zero impedance. The back-e.m.f. and

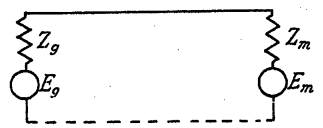


FIG. 26.

impedance of the motor are denoted respectively by E_m and Z_m.

Next we consider that there is a partial short-circuit across the terminals P and Q (Fig. 25) of the load. This forms a single-phase load analysable into two equal balanced 3-phase loads of opposite sequence. The positive-sequence component adds itself vectorially to the motor load; the other, of negative sequence, may be thought of as flowing independently in the system and producing its own independent voltage-drop. The two voltage-drops, one due to negative-sequence and the other to positive-sequence currents, add themselves vectorially just as though they occurred in two systems connected in series. We know that this must be so because of the action of a pair of phase-sequence indicators.

To imitate the system of Fig. 25, when there is a partial short-circuit across PQ, we lay out two single-phase systems, one (marked " positive sequence " in Fig. 27) exactly like Fig. 26 and the other (marked " negative sequence ") having impedance elements equal to the negative-sequence impedances of one star phase of the 3-phase system. The lines shown in Fig. 27 are simple conductors and, of course, include no rotating machines, hence their positive and negative impedances are equal. This is not true of the generator or the motor: when a 3-phase voltage is applied to the terminals of a generator or motor while it is being driven synchronously (say, by an auxiliary belted motor) the ratio of voltage to current (i.e. the impedance of the machine) is usually greater for positive than for negative rotation of the rotor. Since both the generator and the motor actually rotate positively, they produce only positive-sequence e.m.f.'s, and we introduce no e.m.f.'s into the negative-sequence network of Fig. 27.

To determine how the two networks of Fig. 27 should be interconnected, we consider the behaviour of the

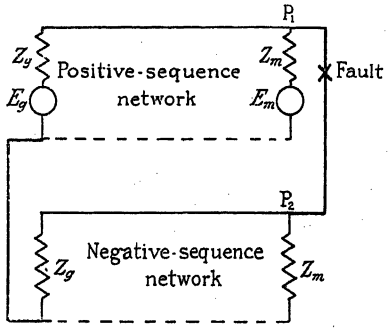


FIG. 27.

fault. As explained in reference to Fig. 14, any single-phase load across two of the 3-phase lines is completely represented by equal positive- and negative-sequence current components. Hence the effect of the fault across PQ is to cause the same fault current to flow through both the positive- and the negative-sequence networks of Fig. 27. To make the fault current pass thus through both networks we join the points P_1 and P_2 which mark the position of the fault, and we put in a return conductor for the fault current; so that, having passed through the positive network and then, via the fault, through the negative network, it can return to the generator. The fault is shown at X. We have to prove that its value must be twice the actual impedance

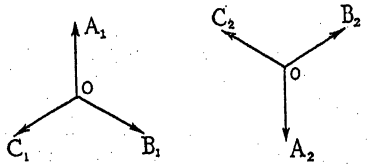


FIG. 28.

of the fault. First, we have to reduce the impedance at X in the ratio 1 : 1·732 of the actual value Z_f, because we are using star voltage instead of line voltage: next, because we are sending through the fault only one of the current components, which amounts to $1/(2 \times 1{\cdot}732)$ of the fault current, we must make the impedance at X $(2 \times 1{\cdot}732)$ times what it otherwise would be.

To obtain the same result vectorially, we consider the two equal 3-phase current sets of opposite sequence to which the single-phase fault current is equivalent (see Fig. 28). The vector sum of OA_1 and OA_2 is zero, that of OB_1 and OB_2 is OB, and that of OC_1 and OC_2 is OC (Fig. 29). The actual fault current is the vector difference of OB and OC, and is equal to $(2 \times 1{\cdot}732)$

times the current of either sequence. As we use in Fig. 27 the current of one sequence only, and instead of

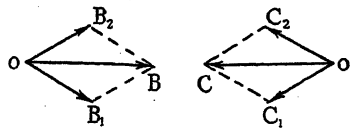


FIG. 29.

the line voltage the limb voltage, we must make the impedance at X equal to twice Z_f.

APPLICATION OF SYMMETRICAL COMPONENTS TO THE PHASE CONVERTOR.

In 1917 E. S. Henningsen* described the phase convertor, referring to the pair of 5 000-kVA units which had been installed in 1916 by the Philadelphia Electric Co. The theory of symmetrical components offers a ready means of explaining the action of the phase convertor, the object of which is to maintain current and voltage balance in the generators in spite of unbalance in the load of a 3-phase system. An obvious solution of the problem is to install a substation containing 3-phase motors coupled to single-phase generators, the latter being used to supply the single-phase load. That method is expensive and inflexible.

The phase convertor is a 3-phase synchronous motor with which is incorporated a 3-phase generator of opposite phase-sequence.

Principle of the phase convertor.—Fig. 30 represents a

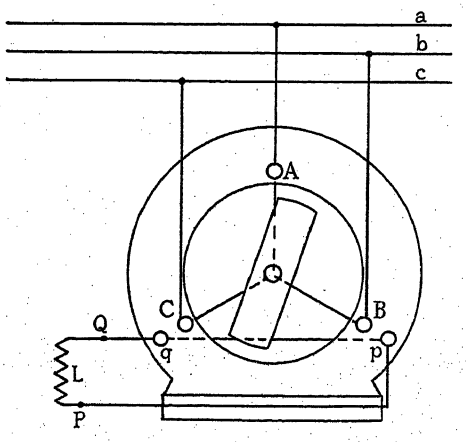


FIG. 30.

2-pole star-connected 3-phase synchronous motor taking energy from the 3-phase line a, b, c. If an extra coil p, q, were laid in the slots BC, it would form a single-phase generator to which a load L might be connected. If L were connected across bc the terminals P, Q, could be joined to b, c. Such a machine would be impracticable without means of regulating the single-phase e.m.f. independently.

The principle of symmetrical components reminds us that a single-phase current may be analysed into two equal 3-phase current sets of opposite sequence. A 3-phase positive-sequence set is available in the stator winding of a synchronous motor. We therefore provide

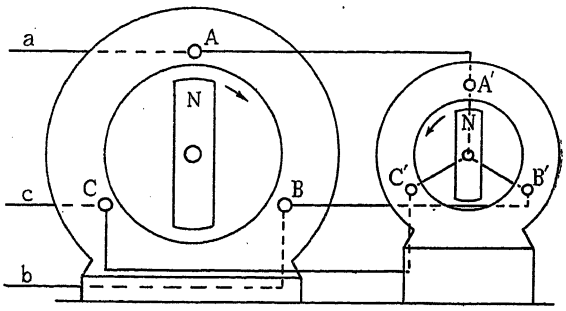


FIG. 31.

another negative-sequence set and put the two in series, as in Fig. 31. For economy of construction the two machines should be mounted on the same shaft, the reversal of sequence being obtained by reversal of

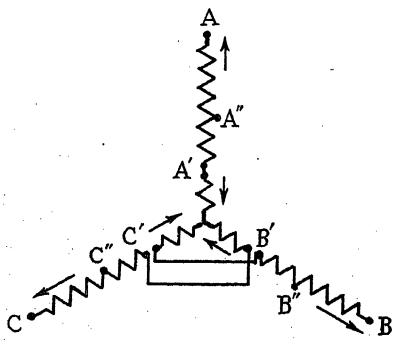


FIG. 32(*a*).

the order of ABC in respect of A′B′C′. The positive-sequence machine ABC is called the motor, the other being called the voltage balancer. The two windings are related as in Fig. 32(*a*). The back-e.m.f.'s of the motor

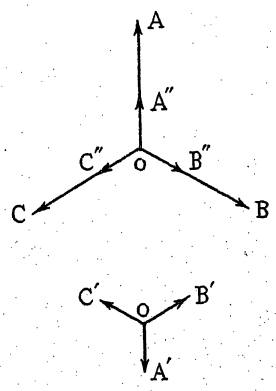


FIG. 32(*b*).

are OA, OB, OC [Fig. 32(*b*)], while the balancer e.m.f.'s are OA′, OB′, OC′. Cutting off at A″B″C″ a positive-sequence star equal to the negative star A′B′C′, we think of these two stars of opposite sequence as combined and giving the resultant PQ [Figs. 32(*c*)]. Now inserting into the vector diagram of Fig. 32(*b*) the

* *General Electric Review*, 1917, vol. 20, p. 479.

line PQ instead of the stars A′B′C′ and A″B″C″ we have Fig. 33. The star Abc in Fig. 33 is the back-e.m.f. of the synchronous-motor element of the system, while PQ is the e.m.f. due to the positive- and negative-sequence elements. This e.m.f. PQ is in phase with the line voltage bc. The vector sum of PQ and that voltage is CB, and it will send into any single-phase load joined across the lines bc, enough current to produce the internal impedance-drop PQ in the convertor. The internal impedance is inductive, and the current required to produce in it the drop PQ must lag on PQ.

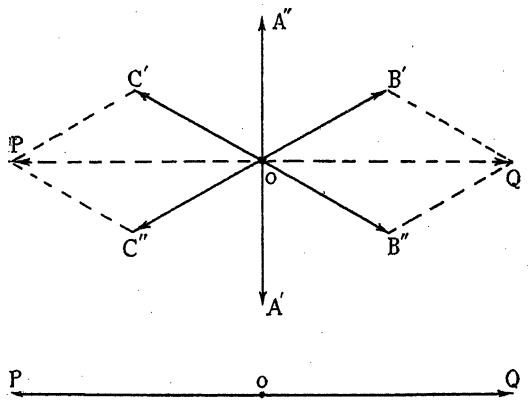


FIG 32(c).

If the single-phase load happens to have this same angle of lag, the whole of the single-phase output will go into the single-phase load; otherwise a part of it will go back into the 3-phase system and the balancing will be incomplete.

If the single-phase load is highly inductive we have to make PQ send a current lagging by a large angle on the line voltage bc. A lagging output current is a leading input current, and hence we have to make the convertor take a leading current. Its synchronous-motor action will make it take such a current if we over-excite it. Conversely, if the single-phase load is capacitative we must under-excite the synchronous-motor element.

Single-phase current taken from two phases.—The case in which equal single-phase loads are taken from the lines ab and bc is simple. We regard this as the taking of a negative load from the remaining phase ac. The convertor will respond to that condition if the balancer element be given a negative excitation.

When unequal single-phase loads are taken from ab and bc the, action of the convertor is less simple: such loads can be made to produce any degree of unbalance. We may imagine that the unbalanced 3-phase load is being supplied by an open-delta generator, for such a machine can take care of any 3-phase load whatever. As a generator of this type has only two windings, it produces only two currents. The magnitudes and the phase relation of these two currents may vary widely, but in every case they may be resolved into two equal currents with a phase difference of 60° (such as a balanced load would take), plus one single-phase current. It is thus necessary for one of the windings of the open-delta generator to carry a single-

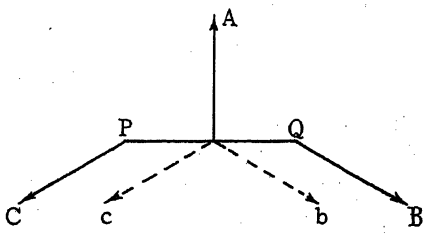


FIG. 33.

phase load in addition to the current which a balanced load would require. This case is thus seen to be similar in principle to that of one single-phase load across the lines b, c.

The action of the convertor is explained above with reference to a single-phase load across the lines bc. To satisfy that case, phase A of the motor element had to be joined to line a. In order to balance a load across ca, phase A of the convertor would have to be joined to line b; or, for a load across ab, phase A would have to be joined to line c. This is because we chose A and A′ as the phases which would cancel each other in the convertor. Thus, for automatic balancing of the 3-phase system, relays must be installed which will control not only the field currents of the convertor, but also the order of its connections to the 3-phase line.

MEASUREMENT OF THE MUTUAL IMPEDANCE OF CIRCUITS WITH EARTH RETURN.*

By JOHN COLLARD, Ph.D., Associate Member.

(*Paper first received 18th December, 1931, and in final form 24th February, 1932.*)

SUMMARY.

The object of this paper is to place on record the results of tests carried out at three different sites in England at which measurements were made of the mutual impedance between two earthed circuits. Results are given for different separations from 5 to 800 metres and for frequencies from 200 to 3 000 cycles per sec. The results are shown to be in good agreement with the theory on this subject, and the resistivity of the earth was found to be 250 ohms/cm³ at one site and 6 000 ohms/cm³ at the others.

INTRODUCTION.

The problem of the mutual impedance of circuits with earth return has received considerable attention in recent years in connection with the study of the inductive interference produced by high-tension power lines and electric traction systems in neighbouring communication circuits. The problem has been investigated theoretically by a number of authors and a fairly complete solution has been produced. A number of practical tests have also been carried out in different countries with a view to checking the theoretical formulæ, and while, in general, the tests have been in good agreement with the theory, the results obtained at certain sites have shown a divergence from the theory. It is thus very desirable, before the theory can safely be applied to the solution of practical problems, that test-results should be made available for as many different sites as possible. This paper has, therefore, been prepared with the object of placing on record the test-results which have been obtained in some mutual-impedance measurements carried out at three different sites in England. These three sites are:—

(*a*) On the marshes at Reculver, near Herne Bay.
(*b*) On the Yorkshire moors, near Goathland, about half-way between Pickering and Whitby.
(*c*) On the shore near Weston-super-Mare.

At this last site, tests were made both at low tide, when the test wires were not covered by the sea, and also at high tide, when the wires were covered to a depth of about 30 ft.

The geological features of these sites are very different, so that the test-results probably cover a wide range of earth resistivity. The more detailed particulars of the different sites and the results obtained are given in the following sections.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

THEORY.

It is not proposed to go into the theory of this subject in any detail since this has already been done by a number of different authors, to whose works reference is made in the Bibliography. Three authors, Pollaczek, Carson, and Haberland, appear to have arrived at a mathematical solution to this problem almost simultaneously and along very similar lines. From these three theories, a series of formulæ have been drawn up by the C.C.I.† giving the mutual impedance between two earthed circuits for a number of practical cases. These formulæ, together with curves plotted from them, are given in their " Directives " published in 1930.

For normal separations the formula for the mutual impedance between two parallel lines with earth return is of the form

$$M = \left\{ -\frac{4}{k^2x^2} + 4\frac{\mathrm{kei}'(|kx|) - i\,\mathrm{ker}'(|kx|)}{|kx|} \right\} \times 10^{-4}$$

In this expression the symbols have the following meanings:—

M = mutual impedance, in henries per km,
x = separation between the two lines, in cm,
$k = e^{\frac{3}{4}\pi i}\sqrt{(4\pi\sigma\omega)}$,
σ = conductivity of the earth, in C.G.S. units per cm³,
e = base of natural logarithms,
$i = \sqrt{-1}$

ker′ and kei′ are the differential coefficients of ker and kei, which are the Kelvin forms of Bessel functions. Tables of these functions are given in British Association Report, 1915, pp. 36–38.

It will be noticed that this expression gives the mutual impedance in terms of the variable kx, k itself being a function of the square root of the frequency and of the square root of the conductivity of the earth. The theory would, therefore, lead us to expect that, for any given value of earth conductivity, the mutual impedance should be a function of the variable $x\sqrt{f}$. In order to show with what accuracy the experimental results agree with the theoretical relations, the test values of mutual impedance have been plotted as a function of the variable $x\sqrt{f}$ and in each case the theoretical curves for appropriate values of earth conductivity have been drawn in. Two sets of curves have been plotted, one set giving the magnitude of the mutual impedance expressed in henrys per kilometre, and the other set giving the corresponding angle of the mutual impedance.

† Comité Consultatif International des Communications Téléphoniques à Grande Distance.

(*a*) *Reculver Tests.*

These measurements were not actually carried out to test the validity of the theoretical formulæ and, since the purpose for which they were required did not necessitate any very great accuracy, a somewhat primitive form of testing apparatus was used. In spite of this the results show a reasonable agreement with the theory and are of interest since they correspond to the case in which the resistivity of the earth is very low.

Description of Site.—These tests were carried out in December 1927 at a site on the marshes situated between the railway and the sea just east of Reculver, which itself lies about 4 miles to the east of Herne Bay. The ground, which is used for grazing purposes, has been drained by a number of intersecting dikes. The site was not ideal for the purpose of testing the theory, since the latter assumes an earth of uniform structure. Actually, however, the results do not appear to show any divergence from the theory which could be attributed to the non-uniformity of the site.

A mile of 0·028-in. vulcanized-rubber-covered copper wire was laid out along the ground in a straight line to act as an inducing circuit. A second length of about ½ mile was used as the induced circuit and was placed parallel to, and near the centre of, the inducing wire and at separations of 30, 60, 150, 300, 600, 1 200, and 2 840 ft. from it. Each wire was earthed at each end by means of earth pins and, owing to the nature of the ground, a low-resistance earth connection was easy to obtain.

Description of Apparatus.—A variable-frequency valve oscillator was connected in one end of the inducing circuit through a transformer arranged to match the impedance of the line approximately with that of the oscillator. The current supplied to the line was measured by means of a thermo-couple, and meter and measurements were made at frequencies of 370, 640, 810, 1 000, 1 500, 1 800, and 2 570 cycles per sec.

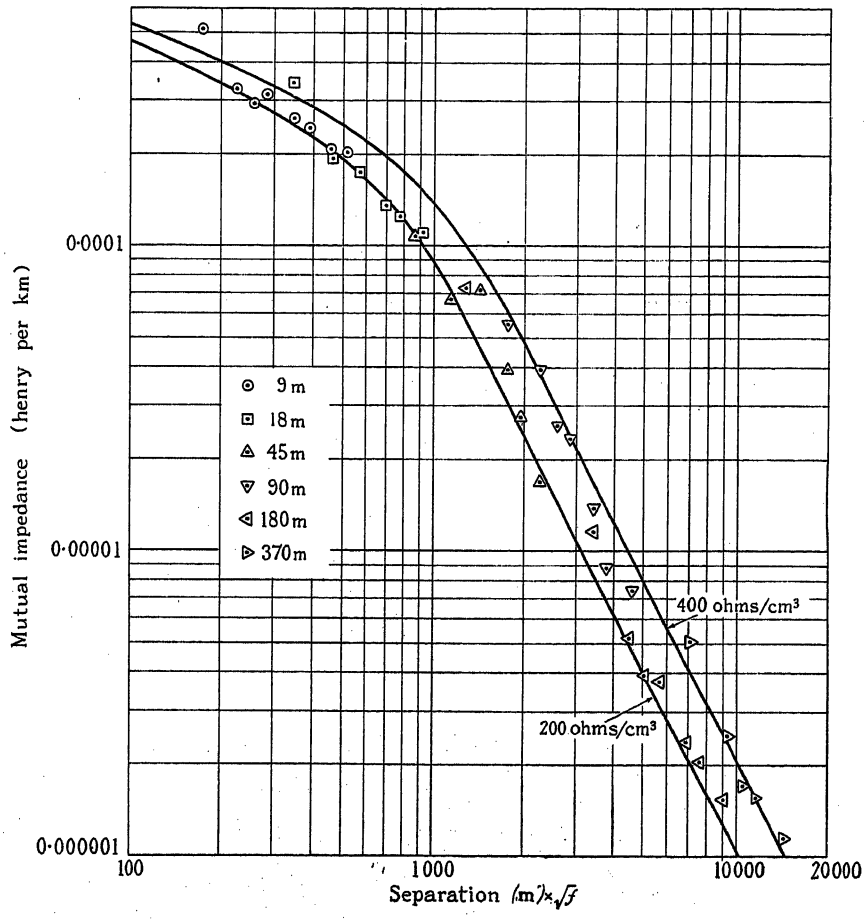


FIG. 1.—Reculver tests.

The measurement of the voltage in the induced conductor was made by connecting an amplifier to the conductor and then switching a telephone receiver alternately to the output of this amplifier and to a second valve oscillator which was set to the same frequency as that supplied to the inducing circuit. By means of an attenuator the output of this second oscillator could be varied until it was estimated that the tone heard in the receiver when connected to the amplifier in the induced conductor was the same as that heard when the receiver was connected through the attenuator to the oscillator. The apparatus had previously been

calibrated in the laboratory so that the relation between the setting of the attenuator and the e.m.f. induced in the conductor was known. It was estimated that the balance could be carried out to within 0·5 decibel. This measurement, of course, only gave the magnitude of the voltage and, since this was all that was required in this instance, no attempt was made to measure the angle.

From a knowledge of the magnitude and frequency of the inducing current, the magnitude of the induced e.m.f., and the length of the induced circuit, the mutual impedances for the different cases have been worked out and are plotted in Fig. 1.

(*b*) *Goathland Tests.*

The results obtained at Reculver, in spite of their rather approximate nature, showed such a reasonable agreement with the theory that it was decided to carry out a second and more extensive series of tests to check this agreement still further. This time it was decided to measure both the magnitude and the angle of the mutual impedance and to use a method giving considerably greater accuracy than that used at Reculver.

Description of Site.—These tests were carried out in June 1928 at a site on the Yorkshire moors about halfway along the Pickering–Whitby road. This site was chosen partly because it enabled a long, straight wire to be laid out and partly because it was so far away from any source of electric power that the effect of stray fields was avoided. A test hut was erected at the point where the road from Goathland joins the main road just north of Eller Beck. It was decided to use an inducing wire 5 miles in length and, as the main road runs for some considerable distance substantially in a straight line, the inducing wire was placed for 2½ miles from the hut in each direction in a shallow ditch which lies on the west side of the road. The only point where it was necessary to divert the wire from the road in order to maintain the straight line was at Eller Beck. Here the wire was laid across the moor and was suspended across the Beck.

A 0·036-in. vulcanized-rubber-covered copper wire was used as the inducing circuit and was earthed at both ends by means of substantial earth-plates. At the centre the wire was cut and joined to a short twisted rubber-covered pair by means of which it was connected with the test hut. The induced wires were laid parallel to the inducing wire, starting at a point level with the test hut and running in a northerly direction. A 0·028-in. vulcanized-rubber-covered copper wire was used for this purpose and was placed at separations of 10, 20, 40, 80, 160, 320, and 575 metres from the inducing wire. For the close separations the induced wire had a length of about 380 m and for the wider separations about 480 m. At the far end the wire was connected to earth pins and at the end near the hut a second earth connection was installed. A twisted pair was then run out from the test hut, one wire being connected to the end of the induced conductor and the other to the second earth connection. The twisted pairs to the inducing and induced wires were run out at right angles to the inducing wire.

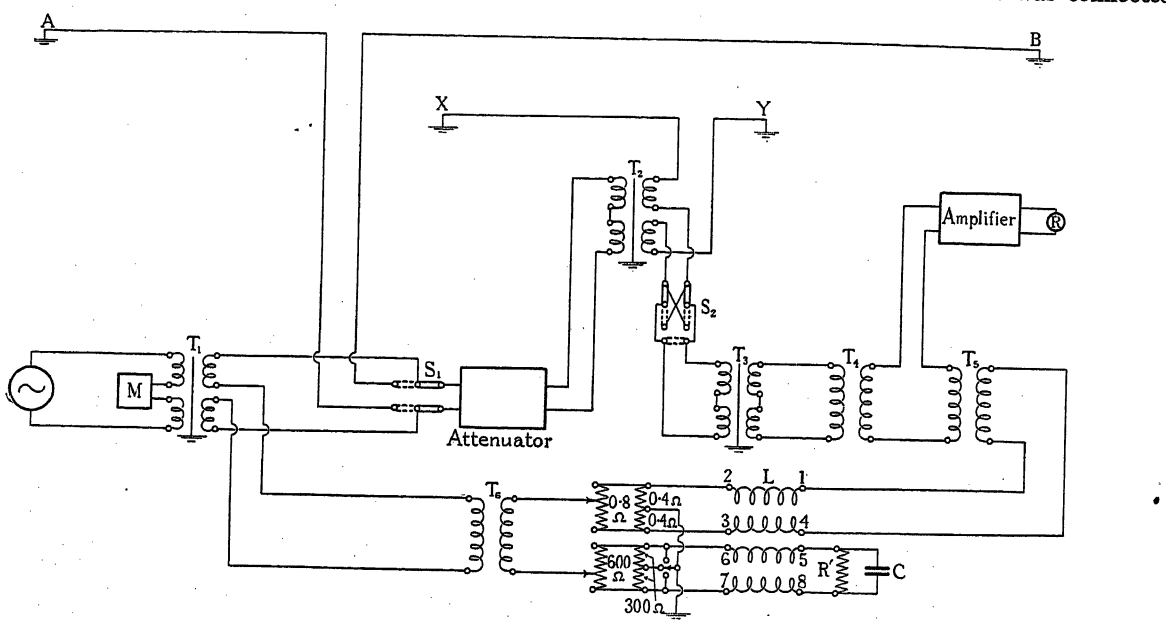


FIG. 2.—Apparatus used for mutual impedance measurements.

The ground in the neighbourhood of the test site was very hard, making it difficult to secure good earth connections. According to geological surveys, it appears to consist mainly of sandstone to a depth of about 600 ft.

Description of Apparatus.—A diagram of the apparatus used for these tests is given in Fig. 2. A variable-frequency valve oscillator was connected to a shielded transformer T_1, M being a thermocouple and meter for measuring the current supplied by the oscillator. The output of T_1 was connected in series with a second transformer T_6 and a switch S_1. The switch S_1 was used to connect the oscillator either to the inducing line

AB or through an attenuator to the shielded transformer T_2. When the tone from the oscillator was switched to the inducing line, an e.m.f. was induced in the induced conductor, XY, and was thence conveyed through the switch S_2 to a shielded transformer T_3 and then through another transformer T_4 to an amplifier and receiver R. At the same time, tone from the oscillator was passed through transformer T_6 to the coupling unit which is shown to the right of T_6. This coupling unit consists of a toroidal inductance L wound on a wooden core and having four windings. The two windings 1, 2 and 3, 4 are connected at one end through a transformer T_5 to the amplifier and receiver and at the other end to a 0·8-ohm slide-wire and two 0·4-ohm resistors in series, with the centre point earthed. The other two windings 5, 6, and 7, 8, of the inductance are connected to a resistor and condenser which are arranged to give these windings a resultant impedance of 600 ohms at all voice frequencies. At the other end, the windings are connected to a 600-ohm slide-wire and to two 300-ohm fixed resistors connected in series. When the moving contact of the 600-ohm slide-wire is in the mid position, no current flows through windings 5, 6, and 7, 8, so that no voltage is induced in the other windings. As soon as the moving contact is moved from the centre position, a certain amount of current flows in the lower two windings of the inductance and thus produces in the other two windings an e.m.f. in quadrature with the oscillator current. The lower and upper pairs of windings are arranged to have a mutual inductance of 300 μH, and, since the lower windings are built out by the resistor and condenser to an impedance of 600 ohms, it follows that, when the moving contact of the 600-ohm slide-wire is moved to one end, the effective mutual inductance is + 50 μH and, when the moving contact is on the other end, the effective mutual inductance is − 50 μH. For settings of the 600-ohm slide-wire in between these points, the mutual is directly proportional to the distance of the slide-wire from the centre. The contact which is normally connected to the centre point of the two 300-ohm resistors may be moved, as shown in the diagram, so as to connect to either end of these resistors and thus adds ± 50 μH to the mutual inductance. The upper slide-wire is provided to produce an e.m.f. in phase with the current. The whole coupling device, which is the invention of Mr. A. D. Blumlein,* thus provides a very simple and convenient means of obtaining a variable impedance of known value. The device has another very important property and that is that, since the inductance is toroidal, it is unaffected by stray magnetic fields.

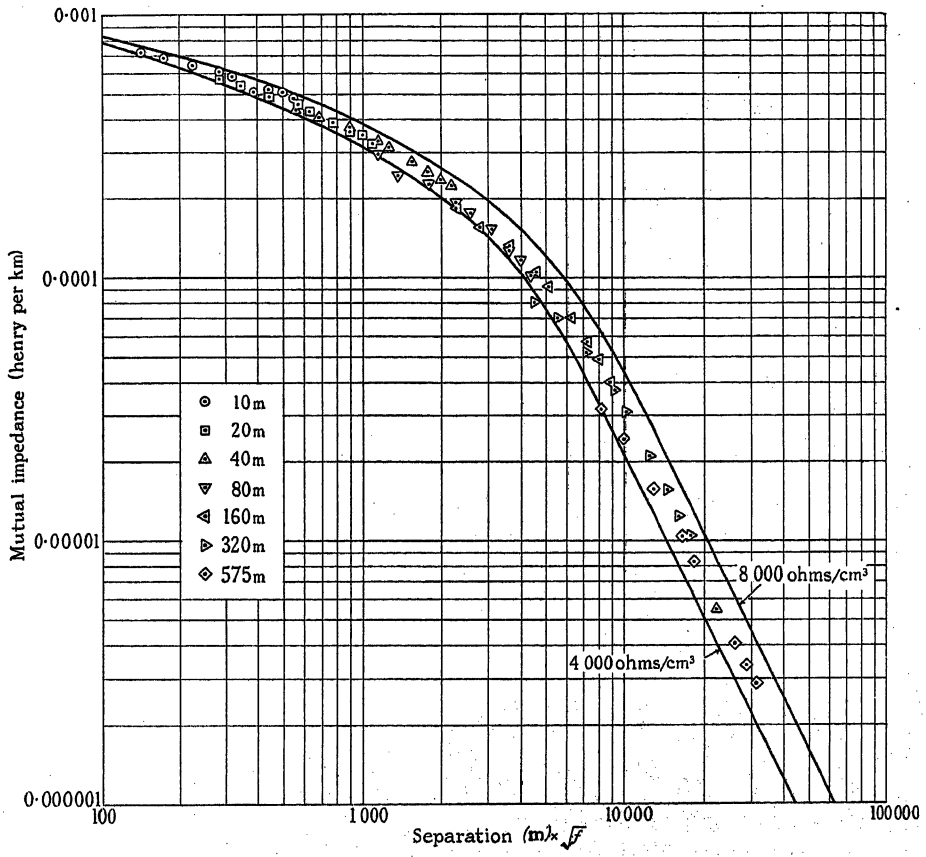


FIG. 3.—Goathland tests.

It is not practicable to arrange this device to cover the very wide range of impedances required in the tests, so that the two transformers T_4 and T_5 are arranged to have their ratios variable in a number of steps. In

* British Patent No. 338588.

making the measurement the ratios of T_4 and T_5 and the settings of the two slide-wires of the coupling unit are so adjusted that the tone heard in the receiver is a minimum.

The transformers, T_1, T_2, T_3, and T_6, are necessary to separate the different parts of the apparatus and so prevent cross-talk from one part of the circuit to another. Their introduction, however, and the capacitance of the twisted pair running out from the test hut to the induced circuit both cause slight changes in the magnitude and phase of the testing currents. It was originally intended to overcome this difficulty by calibrating the apparatus in the laboratory. When the tests on the site actually came to be made, however, it was found that the short showers which occurred covered the twisted pair with moisture, while the effect of the wind in between the showers was to tend to dry the wire. The effect of this constant change in the amount of moisture on the twisted pair was to cause the capacitance of the pair to vary in a very marked and erratic manner.

It was therefore decided to carry out a calibration measurement on the site immediately after each test measurement. For this purpose a small known voltage was introduced into the induced conductor by means of an attenuator and a transformer T_2. The transformer was placed near the induced conductor and was connected back to the hut by a second twisted pair. Since the attenuator was arranged to have an impedance of only a few ohms on the output side, the effect of the variations in capacitance of this second pair was inappreciable. The effect of T_2 on the calibrating voltage was allowed for by previous calibration.

Measurements were made at frequencies of 200, 300, 500, 800, 1 000, 1 500, 2 000, 2 500, and 3 000 cycles per sec. The magnitude of the mutual impedance is plotted in Fig. 3 and the angle in Fig. 4.

(c) Weston-super-Mare Tests.

These tests were carried out in order to obtain further information on the agreement between the theoretical formulæ and practical results. The site at Weston was chosen because it enabled two sets of results to be obtained, the first when the sea was out and the second when the test wires were covered by sea water. The first set of results corresponds to the case of two circuits on the land which had already been tested at Reculver and Goathland. The second set of results corresponds to the case which occurs when two submarine cables run into the same landing place. Inductive interference often occurs in such a case and it was, therefore, considered of interest to determine whether the theory could also be applied to this case.

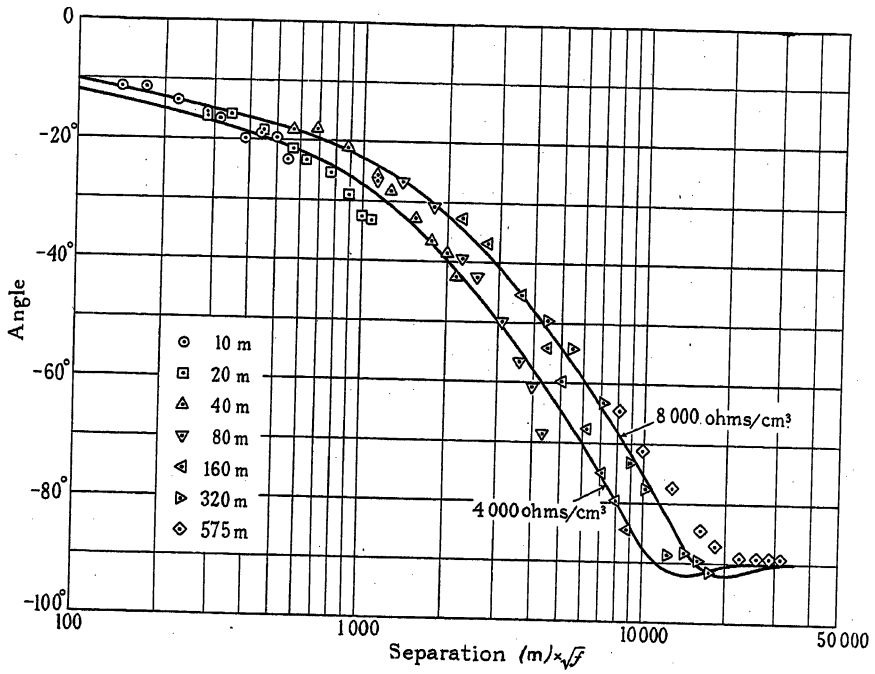


FIG. 4.—Goathland tests.

Description of Site.—These tests were carried out in October 1929 at a point on the shore between Sand Point and St. Thomas's Head about 3 miles to the north of Weston-super-Mare. This site was chosen principally because of the extremely high tide, about 40 ft., occurring there. It was also sufficiently far away from sources of electrical power to avoid stray fields. A stone hut on top of the cliff was used to house the testing equipment, and rubber-covered twisted pairs were run down to the beach to connect with the inducing and induced wires. The inducing conductor consisted of about ½ mile of 3/·029 tough-rubber-sheathed copper wire laid out along the shore and earthed at each end. The induced wires were of the same material and were placed parallel to the induced wire near its centre; their length varied from 100 to 200 yards and they were

earthed at each end. A twisted pair from the test hut was connected into the middle of the inducing wire and another twisted pair into the middle of the induced conductor. These two pairs were kept about 20 yards apart to avoid pick-up from one to the other. Owing to the fact that the wires would all be under water for a large part of the tests, special care was taken in insulating all joints so that water should not penetrate. The wires were kept in place by weighting them down with heavy stones at a number of places, and no trouble was experienced due to shifting of the wires by the sea. The induced wire was placed at the following separations from the inducing wire, 5, 10, 20, 40, 80, and 120 metres.

The wires were laid at low tide and, after the tide had risen, were covered to an average depth of about 30 ft.

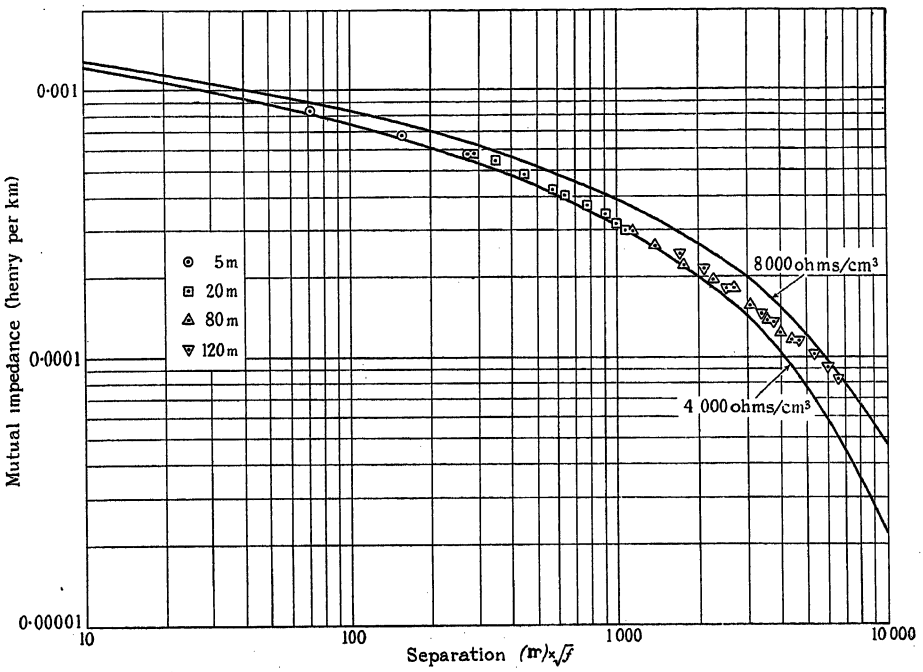


FIG. 5.—Weston-super-Mare tests (low tide).

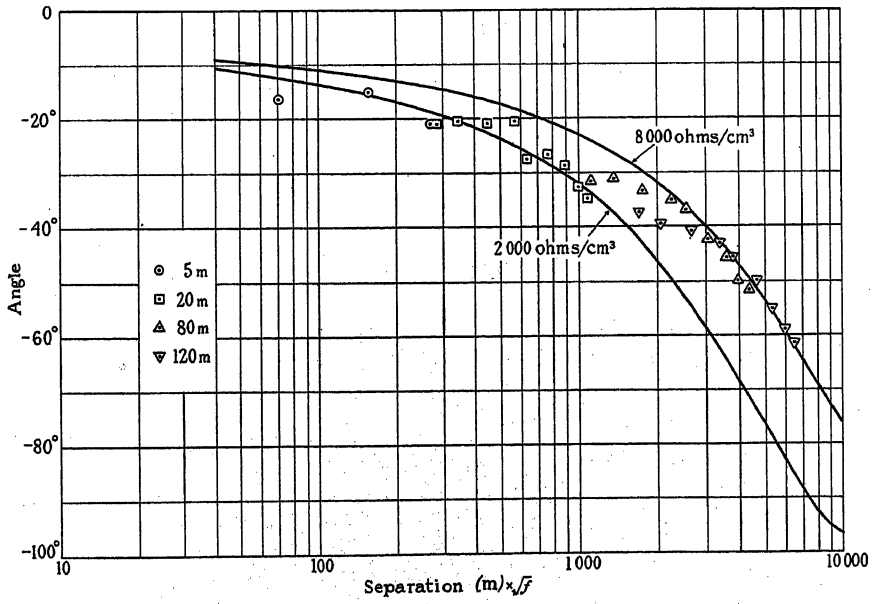


FIG. 6.—Weston-super-Mare tests (low tide).

Description of Apparatus.—The apparatus used for these tests was almost identical with that used at Goathland, so that a detailed description need not be given. The calibrating arrangement was not used this

time since, owing to the shorter length of the twisted pairs and the lower impedance of the inducing and induced wires, the effect of the capacitance of the pairs was extremely small. The apparatus was therefore calibrated in the laboratory before being taken to the site, and a slight calculated correction was made for the capacitance of the pairs.

Measurements of mutual impedance were made at the following frequencies, 200, 300, 500, 800, 1 000, 1 500, 2 000, 2 500, and 3 000 cycles per sec. Two sets of tests were made, one with the tide right out and the other with the tide right in. The magnitude of the low-tide mutual impedances are plotted in Fig. 5 and experimental results all fall within the two theoretical curves, and a mean curve drawn through the points would follow very closely the shape of the theoretical curves. In the case of the angle of the mutual impedance, Figs. 4 and 6, the experimental points appear to deviate considerably more from the theoretical curves, although the general trend of the points follows the line of the theoretical curves. Fortunately, from the practical point of view, we are more concerned with calculating the magnitude of the mutual impedance than its angle, so that deviations of the measured angles from the theoretical curves are of relatively small importance. In any case, the distribution of the points

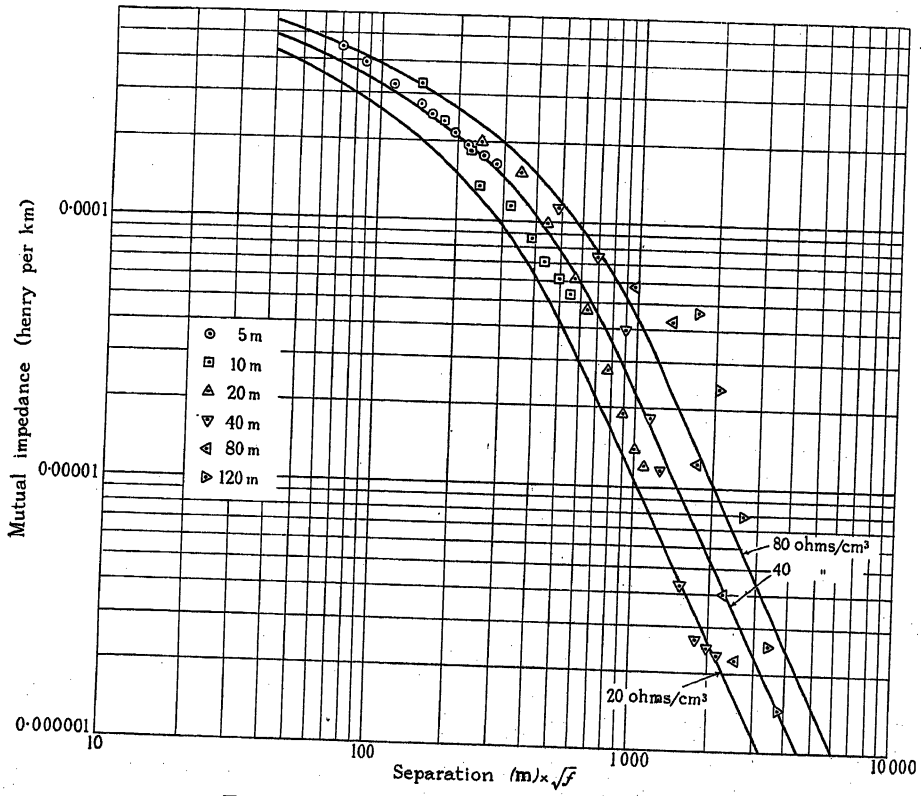


FIG. 7.—Weston-super-Mare tests (high tide).

the angles in Fig. 6. The magnitudes for the high-tide case are plotted in Fig. 7.

DISCUSSION OF RESULTS.

In judging the accuracy with which the experimental results agree with the theoretical curves, most attention should be directed towards the tests at Goathland and the tests at low tide at Weston-super-Mare, since these are the tests which were carried out with the greatest accuracy. These two sets of results have been plotted in Figs. 3, 4, 5, and 6, and in each case two theoretical curves have been drawn in, one for an earth resistance of 4 000 ohms/cm^3 and the other for a resistance of 8 000 ohms/cm^3.

Taking, first of all, the two sets of results for the magnitude of the mutual impedance, Figs. 3 and 5, it will be noticed that, except for a few isolated points, the appears to be quite erratic, which would indicate that the deviations are due more to experimental errors than to any systematic departure from the theory. The results obtained at Reculver, plotted in Fig. 1, will be seen to agree reasonably well with the theoretical curves when the relatively smaller accuracy of these tests is taken into account.

The tests taken at high tide at Weston-super-Mare show considerably greater deviation from the theoretical curves, and there are a number of reasons which would account for this. In the first place, the theory, which was developed for the case in which air and earth were the media, does not strictly apply to the case of wires in the sea. It was thought, however, that if the depth of water covering the wires were large compared with the separation between the two wires, then, since the resistivity of the sea is so much less than that of the

earth (30 ohms/cm^3 compared with 6 000 ohms/cm^3), the case might be considered as equivalent to an inverted air-earth case, that is to say, with the water taking the place of the earth in the normal case and the earth taking the place of the air in the normal case. If this were so, then the same theoretical formulæ should apply. In order to see whether this assumption does hold or not, the experimental points have been plotted in Fig. 7, and three theoretical curves have been drawn in, corresponding respectively to resistivities of 20, 40, and 80 ohms/cm^3. It will be seen that for the points taken at the closer separations the agreement with a theoretical curve for a resistivity of about 30 or 40 ohms/cm^3 is quite good, and actually the resistivity of the sea should be somewhere about this value. For the larger separations, the points deviate rather more from the theoretical curves and this is only to be expected since the depth of water, about 30 ft., is no longer large compared with the separations. Indeed, it is a little surprising that with this small depth of water even the separations of 5 and 10 m are in good agreement with the theory. There seems to be no doubt that, provided the depth of sea water is more than twice the separation between the two wires, the theoretical expressions would approximate quite well to the experimental results.

Tests of mutual impedance carried out in Germany have shown that in order to make the theory agree with the experimental results it was necessary to take a different value of earth resistivity for each frequency. As a result of this, the C.C.I. when making use of the theory for practical purposes have proposed to use a value of resistivity proportional to the square root of the frequency. It is, therefore, of interest to examine the test-results given here to see whether there is any sign of the resistivity varying with frequency. Take first of all the Goathland results, Fig. 3. The maximum variation of frequency employed here was 200 to 3 000 cycles per sec., so that, if the resistivity should vary as the square root of the frequency, we should expect a variation of resistivity of about 4 to 1. If the points for each separation are examined, it will be seen that there is a slight tendency for them to depart from the theoretical curve, the points at the lower frequencies appearing to move over towards the theoretical curve for the lower resistivity. The total change of resistance necessary to account for this effect is, however, nothing like the 4 to 1 just mentioned and is actually only about 1·5 to 1. The Reculver tests, Fig. 1, for which the maximum frequency range was 370 to 2 570 cycles per sec., do not appear to show any sign of this change in resistance with frequency. In the case of the low-tide measurements at Weston-super-Mare with a frequency of 200 to 3 000 cycles per sec., there again seems to be a very slight tendency for a change of resistance with frequency, though it is even smaller than at Goathland and seems to be reversed in the case of the 20-metre points.

Curiously enough, the measurements of angle at Goathland, Fig. 4, seem to require a change of resistance with frequency in the opposite direction, that is to say, a lower resistance for the higher frequencies. In any case, the mutual impedance depends only on the square root of the resistivity. It seems reasonable to conclude, therefore, that for these three sites and for the range of frequencies employed in these tests, a change of resistance with frequency to make the theory fit the experimental results is either not required at all or is so small as to be of negligible importance in practical cases.

Another point of some interest which arises from these tests is the short lines to which the theory, which assumes an infinite conductor, seems to apply. At Weston-super-Mare, for example, the inducing line was only ½ mile and the induced line in some tests only 100 yards.

The test-results show that the following values of the resistivity of the earth give the best agreement with the theory in the different cases:—

Reculver	.. .. ..	250 ohms/cm^3
Goathland	.. .. ..	6 000 ohms/cm^3
Weston-super-Mare	(low tide)	6 000 ohms/cm^3
	(high tide)	40 ohms/cm^3

Conclusions.

The most important conclusion to be obtained from these tests is that the Carson-Pollaczek theory agrees very well with the experimental results in the three sets of tests described here. Furthermore, the variation of the earth conductivity with frequency, if it occurs at all, is extremely small and can therefore be neglected for all practical purposes. The resistivity of the earth has been found to vary from a value of about 250 ohms/cm^3 at Reculver to a value of about 6 000 ohms/cm^3 at Goathland and Weston-super-Mare. This indicates that it is desirable, when applying the theory to some particular site, to know the conductivity of the earth at that site rather than to assume a uniform conductivity for all sites.

The tests carried out at high tide at Weston-super-Mare indicate that, provided the separation between two wires laid in the sea is smaller than the depth of water over the wires, the Carson-Pollaczek theory applies equally well in this case, the sea being considered as the earth and the earth as the air in the normal case. This point is of use in considering problems of interference between adjacent cables in the sea.

Finally, the test-results described here show the desirability of carrying out still further tests in order to obtain a more detailed knowledge of how the conductivity of the earth varies according to the geological nature of the earth and under what conditions it is necessary, as in the German tests, to assume a variation of conductivity with frequency. In this connection it is of interest to note that the Electrical Research Association, in conjunction with the Commission Mixte Internationale, are carrying out similar tests in England at several sites.

In conclusion the author wishes to thank the International Telephone and Telegraph Laboratories, Incorporated, for permission to publish this paper. He would also like to take this opportunity of expressing his indebtedness to those members of the Interference Department of the Laboratories who have assisted in the tests described here, and in particular to Mr. A. D. Blumlein, B.Sc.(Eng.), for his work in developing the testing apparatus used in the Goathland tests.

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INSTITUTION NOTES.

Overseas Members and the Institution.

During the five months ended the 30th September, 1932, the following members from overseas have called at the Institution and signed the "Attendance Register of Overseas Members":—

Adams, P. R. (Calcutta).
Anderson, N. L. (Shanghai).
Atkins, J. W. (Dacca, India).
Bradford, W. B. (Bombay).
Briggs, W. T. (Cairo).
Bulley, H. S. (Calcutta).
Burkinshaw, H. (Madras).
Da Costa, F. A. V. (Sao Paulo, Brazil).
Daw, S. E. H. (Berlin).
Dibben, E. (Bombay).
Donoghue, J. E. (Sydney).
England, C J. (Madras).
Greenwood, E. J. B. (Madras).
Gunn, J. H., B.Sc.(Eng.) (Sydney).
Hale, T. C. (Surat, India).
Hardman, J. (Muar, F.M.S.).
Hawkins, E. J. (Kans, Nigeria).
Hofman, S. P. (Boksburg, Transvaal).
James, E. E. (Lake Coleridge, N.Z.).
Jeffrey, C. S. (Sydney).
Johnstone, A. W., B.Sc. (Eng.) (Nyounghla, Burma).
Kean, A. J. A. (Hyères).
Kennard, F. E. (Colombo).
King, T. G., B.Sc.(Eng.) (Harcourt, Nigeria).
Paine, G. R. (Ipswich, Queensland).
Patrick, W. M. (Shanghai).
Porter, T. Y. (Buenos Aires).
Prescott, W. A., B.E. (Sydney).
Rickwood, H. A. (Bombay).
Roe, G. E. (Nairobi).
Sharpley, F. W. (Dhanbaid, India).
Symes, W. F. S. S., O.B.E. (Athens).
Vacy-Ash, W. M., O.B.E. (Quetta, India).
Whitehurst, J. T. (Montreal).

Students' Quarterly Journal.

The *Students' Quarterly Journal*, which is published each session in October, December, February, and April, is issued free of charge to Students and to Graduates under the age of 28, but other members of any class may obtain it on payment of an annual subscription of 6 shillings, which should be sent to the Secretary of the Institution. The charge to non-members is 10 shillings per annum.

Scholarships.

The following Scholarships have been awarded for 1932–33:—

Ferranti Scholarship (*Annual Value* £250; *tenable for* 2 *years*).

C. D. J. Statham, B.Eng. (Sheffield University).

Duddell Scholarship (*Annual Value* £150; *tenable for* 3 *years*).

P. J. Rattue (Staveley Grammar School).

Silvanus Thompson Scholarship (*Annual Value* £100 *plus tuition fees*; *tenable for* 2 *years*).

W. E. Arnold (London, Midland and Scottish Railway Co.).

Swan Memorial Scholarship (*Annual Value* £120; *tenable for* 1 *year*).

G. N. Davison (Sunderland Technical College).

David Hughes Scholarship (*Value* £100; *tenable for* 1 *year*).

R. G. Armstrong (University College, London).

Salomons Scholarship (*Value* £100; *tenable for* 1 *year*).

J. S. Wright (King's College, London).

Thorrowgood Scholarship (*Annual Value* £25; *tenable for* 2 *years*).

B. O. Banks (Metropolitan Railway).

War Thanksgiving Education and Research Fund (No. 1).

Grants of £50 each have been made for 1932–33 to the following for research purposes:—

G. J. Scoles (University College, London).
T. H. Walker (Sheffield University).

"Notes on the Preparation of Mathematical Papers."

The London Mathematical Society have issued a pamphlet with the above title, for the guidance of authors when preparing the MSS. of mathematical papers for publication. Copies can be obtained from Messrs. C. F. Hodgson and Son, Ltd., 2 Newton Street, Kingsway, London, W.C.2, price 1s. per copy post free. The earlier suggestions of the Society were published in the *Journal* in 1916 (vol. 54, p. 120).

Proceedings of the International Conference on Large High-Tension Electric Systems.

The Proceedings of the 1931 Session of the Conference have now been published. They consist of three bound volumes, totalling 2 500 pages, and can be obtained from the Secretary of the Conference, 54 Avenue Marceau, Paris, price 380 francs. The Proceedings, which are in French, comprise the 100 papers presented at the Conference, with the discussions.

Volume 1 deals with the construction of generating and transforming equipment.

Volume 2 deals with the construction, insulation, and maintenance of transmission lines.

Volume 3 deals with network operation, protection, and interconnection; reactive power; earthing; voltage surges; lightning protection; metering; parallel operation; and selective protection.

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FAULTS, AND THEIR CLEARANCE ON LARGE NETWORKS.

By REGINALD O. KAPP, B.Sc., Member, and C. G. CARROTHERS, B.Eng., Associate Member.

[*Paper first received* 13*th August*, 1931, *and in final form* 28*th January*, 1932; *read before* THE INSTITUTION 7*th March*, *before the* WEST WALES (SWANSEA) SUB-CENTRE 26*th February*, *and before the* TEES-SIDE SUB-CENTRE 9*th March*, 1932.]

SUMMARY.

The features of large networks which are important in the design of selective protective systems are discussed.

The characteristics of distance protective relays are considered, and the causes which lead to inaccuracy in their operation are enumerated. It is shown that nearly all these causes are due to the network and not to the relays. The conditions governing the minimum safe clearance times and minimum length of line that can be protected are discussed.

An analysis is given of the magnitude and distribution, between earth and the conductors, of earth fault currents on systems with multiple earthing of the neutral point, and the sources of error resulting from this distribution and means of compensating for this error are given.

Protective systems depending on direction of fault current are discussed and the "duplex" system is described in detail. It is shown in what way the conditions in a network during a fault may tend to occasion incorrect operation of relays of this type, and how such tendencies may be overcome in the design of the protective gear.

The difficulties in the design of protective systems introduced by the distortion of the vector diagram during a fault are explained, and it is suggested that these difficulties may be overcome if the distortion itself is used for relay operation, as may be done by employing negative and zero phase-sequence components.

INTRODUCTION.

When a collection of isolated distribution networks come to be linked together a greater change is introduced than the mere addition of a certain mileage of transmission line to the aggregate of component networks. These are welded into a single engineering unit in which every portion responds in some way to changes in every part. The properties of such an interconnected system must be studied as the properties of any single machine are studied. The large amount of generating plant working in parallel, its haphazard distribution, and the extensiveness of the area covered, introduce a number of problems that either do not occur in smaller engineering units or are comparatively unimportant when they do occur.

The authors propose to deal in this paper with a few of the problems arising out of a study of fault currents on such large systems and the bearing of these problems on the design of the gear employed for the automatic isolation of a faulty portion of the network. Such a study is not so important for smaller and simpler units of power distribution. The means that can be adopted for the selective protection of these, such as various forms of overload relays or derivatives of the Merz-Price system, are not very greatly affected by the nature of fault currents. But such means of protection are neither economically nor technically the ideal ones for very large networks. For these, so-called distance protective systems or combinations of directional and overload relays have been found to be cheaper and more satisfactory and have been greatly developed during recent years. Their proper design necessitates a very much fuller knowledge of the value and distribution of the currents and voltages occurring during a fault than did the older methods of selective protection.

PART 1. PROTECTIVE SYSTEMS DEPENDENT ON DISTANCE OF FAULT.

THE PRINCIPLE OF DISTANCE PROTECTION.

It will be convenient for discussion of the influence of magnitude and distribution of current and voltages during a fault to recapitulate briefly the general principle of operation of distance protection, even though this will involve restating a certain amount which has been published already.

All distance protective systems employ relays for clearing a fault, and their time of operation increases in some way with the distance of the fault from the relay. The relays on the faulty section are arranged thereby to reach the tripping position before those on more distant sections. As soon as the faulty section has been cleared all other relays on the system return to their starting position. Distance protection therefore works on the "time graded" principle, but the time grading is made dependent upon the distance from the fault.

The impedance and reactance of the circuit between the relay and the fault are functions of the distance, and therefore the relay is so arranged that its operating time is dependent upon the ratio of voltage to current occurring during the fault. Some systems make the operating time dependent on the ratio of the reactive component of the voltage to the current, so that any variation in the resistance of the circuit, due, for instance, to an arc, does not affect the relay operating-time.

DISTANCE RELAY CHARACTERISTICS.

The principle will be more readily understood by reference to Figs. 1(*a* and *b*) and 2, showing characteristics of distance relays. In these figures the abscissæ represent distance, and the ordinates time.

Points A_0, B_0, C_0, D_0, are switching stations on a portion of a network, the distances between them being proportional to the section lengths. The thin lines a_1, b_1, c_1, represent the tripping times of the protective relays at stations A_0, B_0, C_0.

Fig. 1(*a*) is drawn for relays having a straight-line characteristic in which the time the relay takes to reach

the tripping position varies directly with the distance, with allowance for a constant initial time A_0–A_1.

After the relay contacts at station A have closed to energize the circuit-breaker tripping coil, a certain appreciable time, while the circuit-breaker contacts are opening, must elapse until the circuit is interrupted. This time is represented by A_2–A_1, and so the thick lines A_2, B_2, C_2, represent the times taken for clearing a fault at distances corresponding to measurements along A_0D_0 from A_0, B_0, and C_0 respectively.

It is convenient to call the thin lines " tripping characteristics " and the thick lines " clearance characteristics."

Supposing, for instance, that a fault occurs at X_0 on the short section B_0C_0, the relay at B_0 will energize the

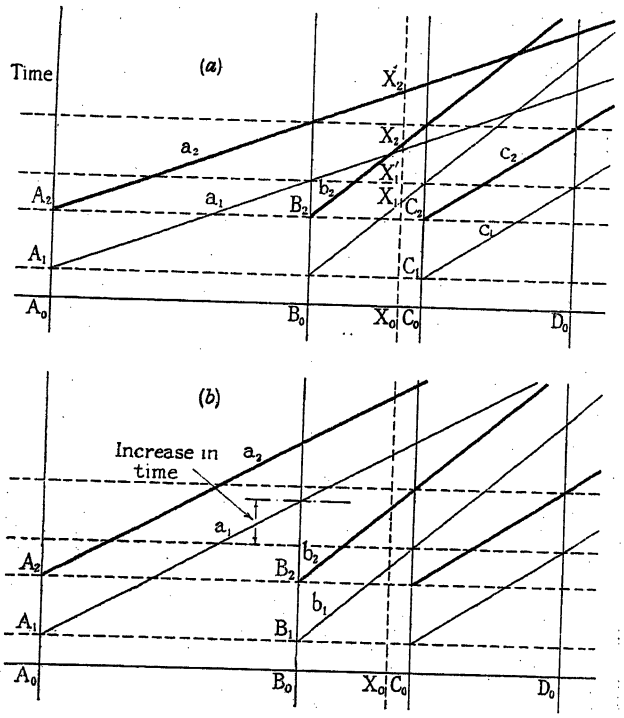


FIG. 1.

(a) Distance relay characteristics giving false operation.
(b) Distance relay characteristics with increased times to avoid false operation.

trip coil of its breaker at a time corresponding to X_1 on the tripping characteristic, and the fault at B_0 will be cleared at a time corresponding to X_2 on the clearance characteristic. As the diagram Fig. 1(*a*) is drawn, the trip coil of the breaker at A_0 will be energized at a time corresponding to X_0, and, therefore, the breaker at A_0 will start to open before the fault is cleared at B_0, and will have finished opening at X_2'. The section A_0B_0 will, therefore, be wrongly cleared. A false operation must always occur if the tripping characteristic on a sound section cuts the clearance characteristic on a faulty section. It will be seen from a glance at Fig. 1(*a*) that in order to guard against such a false operation, as is inevitable with this diagram, it is necessary to arrange for the characteristics on the long sections to be much steeper than those drawn, as shown in Fig. 1(*b*). A steeper characteristic means, however, a longer clearance time.

It is easier to prevent the characteristics from crossing if they are not straight lines, and relay manufacturers have devised gear with curved or kinked characteristics to combine short clearance times with greater discrimination. As an illustration of the properties of such characteristics, Fig. 2 may be mentioned.

(1) The clearance time is as short as possible for faults close to the station and within a distance marked by the point 1. This is an advantage, as it is desirable that faults near a station should be cleared more quickly than if they are far away. Faults in the vicinity of the station reduce the voltage more, and therefore have a more disturbing effect on running plant and the stability of the system.

(2) The characteristic cuts the line corresponding to the next switching station at right angles between points 2 and 3. Any smaller inaccuracy in the characteristic may bring point 2 nearer to, or further from, the line of B_0 on Fig. 2, but will not affect the clearance time for a fault in the vicinity of station B_0. If the characteristic cuts the line corresponding to the station at the end of the section at a sharp angle a small inaccuracy means a large variation in clearance time and, therefore,

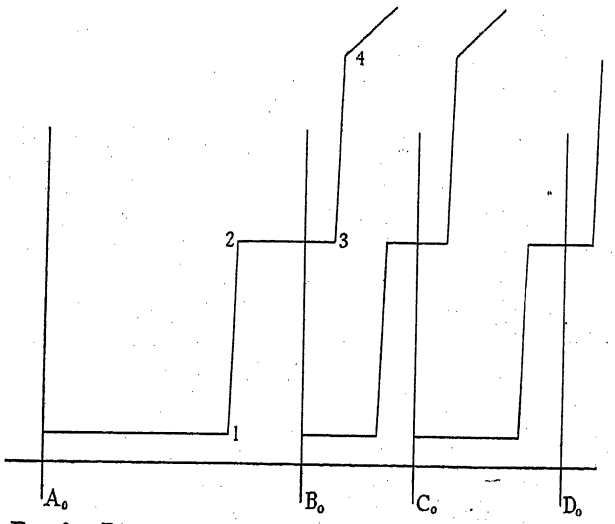


FIG. 2.—Distance characteristics shaped to avoid crossing.

the risk that the conditions as shown in point 1 may be reached, where the relay operates with a fault on the adjoining section before the breaker on that section has cleared. If, however, the range of inaccuracy exceeds the distance between points 2 and 3, this advantage disappears. It will be seen below that this may well be the case, so that the advantage of a horizontal portion 2–3 is at least somewhat doubtful. On very short sections such as B_0C_0, point 3 of one characteristic may come dangerously close to point 2 of its neighbour.

(3) The characteristic slopes steeply upwards between points 3 and 4, thereby reducing the risk of false operation on this part of the curve.

(4) The characteristic becomes flat again from point 4 onwards, and thereby ensures that the relay will clear a fault eventually, after not too long a lapse of time, if for one reason or another the breakers in the vicinity of the

fault should fail to clear. A portion of healthy network is thus cut out, together with the faulty part, but the operation saves the remainder. The distance relay on the adjoining sound section is said to " back up " the one on the faulty section.

All the advantages enumerated above and illustrated in Fig. 2 are not of equal importance, and they are not obtainable with every protective system.

The authors do not wish to suggest that a system which does not embody all of them is necessarily inferior to one which does. The distance/time characteristic is not the only, and not, perhaps, the most important feature of a distance protective system, but it is one which needs thorough study in conjunction with an investigation into the nature of the fault currents and voltages.

Maximum Clearance Time.

The longest clearance time obviously occurs when the fault is at the far end of the section protected, and this

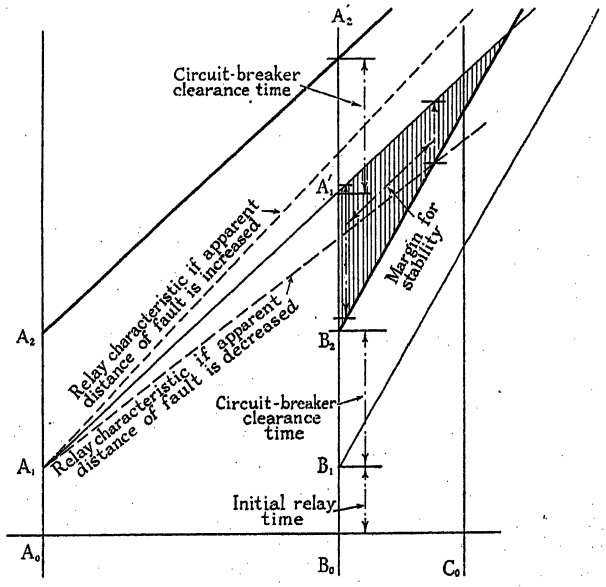


Fig. 3.—Analysis of maximum clearance time.

is given in Fig. 3 by the point A_2'. The least safe value that may be given to this is important. Although long fault-clearance times have been considered permissible in the past, especially in Continental countries, opinion is now becoming almost unanimous that a good protective system should be able to clear faults with as little delay as possible. Suppose a fault is on A_0B_0 and close to B_0. The breaker at A_0 will clear after a time equal to B_0A_2'. It is seen from the diagram that this time is made up of the following parts:—

B_0–B_1 = initial relay time.
B_1–B_2' = circuit-breaker clearance time at B_0.
B_2'–A_1' = margin required for stability.
A_1'–A_2' = circuit-breaker clearance time at A_0.

From this the simple rule follows that the clearance time for a fault at the end of a section is equal to twice the circuit-breaker opening-time, plus the initial relay time, plus a margin. It will be seen below that a number of indeterminate quantities make rather a large margin necessary, and, for this reason, it is not considered safe at the present state of knowledge to set the relay characteristics to give a shorter clearance time than 1·5 to 2·0 seconds for a fault at the far end of a section.

Reasons for a Margin.

It is of interest to consider what factors introduce possible errors into the relay operation. If every portion of the protective devices and the systems protected were perfect and determinate, no margin would be necessary. The margin is necessary because one cannot be certain that such points as 1, 2, and 3, in Fig. 2 will occur on each section at exactly the place where it is intended that they should occur. If these points move far enough from their proper place on the diagram the tripping characteristics of a sound section will encroach on the clearance characteristics of the neighbouring faulty section as they do in Fig. 1(*a*), and thereby produce an incorrect operation, generally known as instability of the protective system. The margin has to be large enough, therefore, to allow for any possible departure between the real position of the relay characteristics and their theoretical position. The possible causes of such departures are as follows:—

(1) The distance relay itself may be a little more rapid, or a little more sluggish, than is intended. In other words, its operating time may not be exactly the required function of the voltage and current supplied to it. Tests on the best British and foreign distance relays show that the margin needed to allow for such imperfections in the relay itself is extremely small. Repeated results lie remarkably closely on the same curve.

(2) The relay characteristic must be adjusted in each case for the length of the section to be protected. It is impossible to obtain an absolutely perfect adjustment, and rather a large margin should be allowed for inevitable errors under this heading.

(3) Both the impedance and the reactance of the circuit between the relay and the fault are not absolutely determinate, particularly for earth faults on a system with the neutral earthed at several points. The reason for this is that the resistance and reactance of the earth return path is a variable and somewhat unpredictable quantity. It is found that earth-fault currents on large networks, where the fault may be at a considerable distance from the nearest earthed neutral point, penetrate many miles into the earth, so that the total circuit forms a loop of large diameter and notable reactance. The depth of penetration and, therefore, both the resistance and reactance of the fault circuit, are functions of the resistivity of the earth. This is found to vary between a few hundred ohms per cm cube and more than 200 000 ohms per cm cube.

From this consideration one might expect that the impedance of the earth-return path would vary between very wide limits. If it did, one would have either to allow enormous margins or to adjust the characteristic of each distance relay in accordance with the resistivity of the earth on each section. This is not generally known even approximately and it depends, moreover, slightly on the surface moisture. It is, therefore, influenced

by seasonal, and even momentary, weather conditions. Fortunately for the art of distance protection, the impedance of the earth-return path varies but slightly, even when the earth resistance varies between extreme practical limits. A full analysis of the subject has already been published in the *Journal*.* It will be seen from Table 4 in the paper referred to that with a variation in the resistivity of the earth between 500 ohms per cm cube and 20 000 ohms per cm cube, the impedance of the circuit may vary by 9 per cent. The uncertainty introduced by earth resistance is, therefore, no greater than can be readily allowed for in a reasonable margin when setting the relay characteristics.

(4) On a system the neutral point of which is earthed at many places, the earth-fault current has two alternative paths, which will be described in detail below. These alternative paths have each a different reactance, so that the total reactance of the circuit depends on the amount of current in each of them. It will be seen below that the distribution of the current between the alternative paths is in itself not constant or determinate, but depends on the amount and distribution of transforming and generating plant on the system. Though the error due to this cause can be largely compensated for, the ratio of voltage to current supplied to the distance relay cannot be quite a true measure of the distance of the fault.

(5) The currents supplied to the distance relay are derived from current and potential transformers, and represent, therefore, the current and voltages in the power line accurately only in so far as the instrument transformers are accurate. The relay is called upon to operate under fault conditions when the voltage is low and the current is high. These are the most unfavourable operating conditions for the instrument transformers, and some appreciable inaccuracy due to this source is therefore inevitable. So long as the fault current does not vary to a great extent above or below a predetermined value the current-transformer accuracy can be made reasonably good. If, however, the fault currents are likely to be very large under certain circumstances and very small under others, the accuracy of the protection cannot be so great. Where the neutral point of the system to be protected is earthed through a high resistance the earth-fault currents will be very much smaller than the phase-fault currents, and one cannot expect current transformers to reproduce both with complete faithfulness. For this reason a system with high neutral earth-resistance is more difficult to protect adequately than a system in which the neutral points are solidly earthed. Similarly, the system on which the total reactance of the circuit may vary between wide limits is more difficult to protect. For instance, if the amount of plant connected varies very greatly, or if the number of transformers through which the system is fed varies greatly, difficulties as regards the protection are introduced.

(6) The breaker opening-time may be longer than allowed for in the relay settings. A more rapid opening-time always improves stability; a sluggish breaker reduces it.

(7) Where the relays are of the impedance type the arc resistance may introduce an unknown ohmic value into the path of the fault, making its apparent distance greater than the true value by an unknown amount. Where the relays are of the reactance type this error is eliminated, but against the gain must be set off the further error introduced by the appliances used to separate out the reactive component of the fault current and the phase-angle error in the instrument transformers.

* P. D. MORGAN and S. WHITEHEAD: *Journal I.E.E.*, 1930, vol. 68, p. 867.

APPARENT DISTANCE OF THE FAULT.

A distance relay responds to the ratio of the secondary currents supplied to it from potential and current transformers. If we assume, as we are justified in doing, almost perfect action on the part of the relay itself for all but quite low voltage and current values, the relay behaves in its timing as if this ratio were proportional to the distance of the fault. In any case, where the ratio of the secondary currents is not a true measure of the distance of the fault, we may speak of this ratio as being a measure of the *apparent* distance. The difference between apparent and true distance might be taken account of in the graphical representation of the relay characteristic by a suitable alteration to the horizontal scale to which this characteristic is drawn, or, alternatively, by a displacement of the characteristic as shown by the dotted lines in Fig. 3. If the apparent distance is greater than the true distance every point on the characteristics shown in Fig. 3 will move further to the left, and the clearance time for a given distance will be increased. If the apparent distance is less than the true one, clearance times will be reduced.

The stability of the system is jeopardized if the difference of the apparent from the true fault distance is such as to cause relay characteristics to cross on the faulty section. If the apparent distance is uniformly reduced all the characteristics are flattened and come nearer together. The stability margin is encroached upon. If the apparent distance is uniformly increased the characteristics all become steeper. They move further apart and the risk of a false operation is reduced. But this is at the cost of increased clearance time. The worst condition is if the apparent distance is increased on the faulty section and reduced on a neighbouring sound section, while the ideal condition is that, conversely, the apparent distance should be reduced on the faulty section and increased everywhere else. So far no protective system has been devised by which this ideal can be ensured with certainty for all operating conditions, and so the designer should aim at reducing the difference between real and apparent distance as much as possible.

In considering the necessary margins to be allowed for stability, the maximum possible variations in the apparent distance of the fault have to be estimated. These are due to the seven possible sources of error enumerated above. A theoretical estimate of the possible magnitude of each of these can only be very approximate. Until more operating experience has been gained, it is impossible to say how small the margin in the relay setting may safely be made. Margins bringing the clearance time for a fault at the end of a section up to 1·5 or 2·0 seconds assume divergencies of several miles of the apparent from the true fault distance. In the authors' opinion more optimistic assumptions

may be safe in future, but ought not to be made at present.

Quantitative Effect of Inaccuracies.

In order that the effect of any source of inaccuracy may be estimated, a scale connecting distance and time is required. We can only consider this subject here in its broad outline. The simplest scale is provided when the relay characteristic is a straight line, as in Fig. 3. An average setting for a distance relay is such that the relay time for a fault at the far end of the section is 1·0 second. This gives us our scale, which is different for every section. The section length, whatever it may be, is equivalent to 1·0 second.

If the fault is at the far end of a section an error of 10 per cent in the fault distance will encroach on the stability margin by 0·1 sec. If the fault is nearer an error of 10 per cent will have a smaller effect.

If the error in the apparent distance is expressed in miles, the effect of an error of 1 mile is dependent on the section length. It is less on long than on short sections. On a section 20 miles long, for example, 1 mile is equivalent to $1 \cdot 0/20 = 0 \cdot 05$ sec. On a 10-mile length, an error of 1 mile encroaches on the stability margin by twice this amount, or 0·10 sec.

Some sources of error, such as arc resistance, are more readily expressed in ohms than in miles. On an overhead transmission line a resistance of 1 ohm is very nearly the equivalent of 1 mile of line. Each ohm of arc resistance would increase the relay time on a 20-mile line by less than 0·05 sec., as the addition is made vectorially.

Minimum Length of Line that can be Protected on the Distance Principle.

All distance protective relays are really ohmmeters, and it is obvious that there is a minimum value of the ohms they can measure to give the requisite degree of accuracy. The practical conditions of operation and maintenance necessitate the sacrifice of sensitiveness to robustness. When the distance of the fault is small they are, therefore, bound to behave as if the fault were at no distance at all. This is one reason why there is a lower limit for the length of line that can be protected. If the section length were below this limit, the relay could not discriminate between a fault on its own and a fault on the adjoining section.

The distance at which the time-grading feature of the distance protective relay begins to come into operation is quite small. If the sensitiveness and accuracy of the relay itself were the limiting feature, very short lines could be adequately protected by almost any make of British or foreign relay. It would, however, be a mistake to consider it safe to employ distance protection on sections of so short a length. The limiting factors are all beyond the relay maker's control. Even relays of laboratory sensitiveness could not protect sections materially shorter than is possible with the commercial instruments now available. The shortest length that can be safely protected depends on the properties of the network and not on those of the protective relays.

It has already been explained that errors in the apparent distance of the fault are the chief reasons why a stability margin in the time setting is required. On a 20-mile section an error of 1 ohm (or about 1 mile) accounts for about 0·05 sec. of this margin. On a 2-mile section length the same error would encroach on the margin by 0·5 sec. The seven sources of error enumerated above may combine to introduce an error far greater than 1 mile, and a stability margin of several seconds would therefore be necessary with the most perfect relay in order to protect lengths as short as 2 miles.

It is generally assumed that the minimum section length that can safely be protected is 10 to 12 miles. From what has been said above, it follows that on such a section length an error of 1 mile encroaches on the stability margin by about 0·10 sec. If the stability margin is 0·5 sec. the maximum permissible error is 5 miles. This error need not be all on one section. The apparent fault distance may increase by 3 miles on the faulty section, for instance, and may be decreased by 2 miles on the neighbouring sound section. It is not the absolute error but the difference between errors on adjoining sections that produces crossing of the characteristics and false operation. Such crossing is less probable when all the characteristics start parallel, i.e. when all the sections are equally long, than when, as in Figs. 1(*a*) and 1(*b*) or Fig. 3, the section lengths are unequal. Then the characteristics are steeper on short than on long sections and it takes less error to cause them to cross. If it is safe to go down to 10 miles on sections of equal length, the minimum safe distance for sections of unequal length should be above this figure.

Another factor influencing the length of section that can be protected is the voltage gradient under fault conditions. All distance relays depend upon a voltage element which exercises a restraint or introduces a feature which has the same effect as a restraint on the current element. Under fault conditions the voltage is necessarily far below the normal line voltage. How far below it will be, depends on two things, (1) the vicinity of the fault, and (2) the value of the fault current. If the latter is small, even a distant fault will bring the voltage down to a very low value. It is possible that this value may be so low as to render the voltage restraint in the relay virtually inoperative, even though the fault is on a neighbouring section. The condition for instantaneous tripping exists on the sound section as well as on the faulty one. This risk is greater with characteristics like that in Fig. 2 than with straight-line characteristics as in Fig. 3. When the fault current is great the voltage gradient is steep. The relay will have an effective voltage restraint even if the fault is fairly near. Even if the protected section is short and the fault just beyond it, the relay will not operate instantaneously and thereby bring out its own sound section, but if the fault current is small it may do so. For this reason the section length that can be protected is shorter for large than for small fault currents. Heavy fault currents occur more often on high-tension than on low-tension lines, and more on lines connected direct to big generating plant or supplied through large transformers, e.g. the British 132-kV "grid." Small fault currents occur on lines fed through comparatively small transformers of high reactance, and, as far as

earth-fault currents are concerned, particularly on systems the neutral point of which is earthed through a high resistance. Such systems are by far the most difficult to protect on the distance principle, and reliable protection can only be obtained if the section lengths are comparatively large. The 132-kV lines of the British grid are far easier to protect, and shorter sections are therefore permissible.

It will be seen from the above that it is impossible to say what is the minimum length of a section to be protected, without knowing at least the length of the adjoining sections and the upper and lower limits of the fault currents. As a general rule 10 miles might be assumed for ideal conditions, and something should be added to this figure where the adjoining section is very long or the earth-fault current small.

Voltage Gradient.

Fig. 4 shows a portion of a line having a generating station at B. The broken sloping line represents the voltage in the transmission line. The fault is at X, and at this point the voltage collapses and becomes zero.

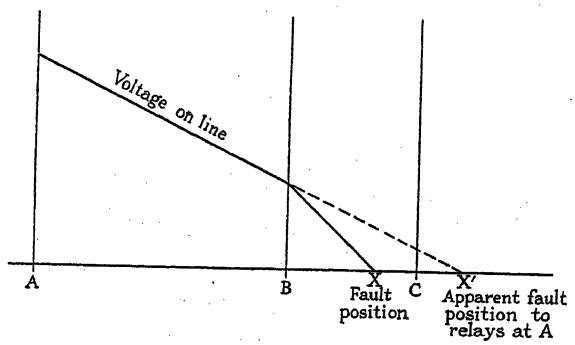


Fig. 4.—Effect of apparent fault position of current fed into line at B.

Some of the fault current is fed from A, but a portion of it is introduced into the line at B, and, in consequence, the section BX carries more fault current than the section AB, and the gradient of the voltage curve (which is proportional to the current in the line) is steeper between B and X than between A and B. Any relay at A operating by the ratio of the voltage at A to the current in the line AB will behave in its timing as if the fault were at X'. For the relay at A, therefore, the apparent fault position is very much greater than the true one. For the relay at B, however, the apparent fault position is at X and coincides with the true one if we neglect other causes of difference. The effect of the generating plant at B is, therefore, to slow down the relay at A, or, in other words, to increase the stability margin. Generating plant at stations immediately adjoining a faulty section has the effect of increasing the apparent fault distance for relays on the sound sections, and is, therefore, an aid in the design of distance protective systems. If the fault on section BC is very near B, this benefit, of course, disappears. It is, therefore, not safe to reduce on this account the margins in the time setting of the relays.

If there is no generating plant at B, but only a transforming station, there will be no kink in the voltage curve as shown in Fig. 4 for phase faults, nor will there be such a kink for earth faults if the neutral point of the transformers is not earthed; but it will be seen below that when the neutral point of the transformers is earthed at several places, and there is magnetic phase coupling between the transformer windings, a similar kink occurs. It will be more convenient to give the explanation later on, but the resultant fact may be noted here that the transformer itself becomes a source of earth-fault current and maintains the voltage as shown in Fig. 4, as if the generating plant were at B. On the British 132-kV grid every transformer is star-connected on the higher-voltage side and the neutral point is solidly earthed. The lower-voltage side is mesh-connected, and, therefore, every one of these transformers is as good as a generating station in helping the stability of distance protection on earth faults. A station with transformers only differs from a generating station, however, in that it gives no assistance on phase faults.

Proportion of Fault Current Contributed by Each Transformer.

It might be suggested that the contribution of current from the station next to the fault will be insignificant if a large number of other stations also supply fault current. Examination shows, however, that this is not likely to be generally true. Suppose that a string of stations feed into the same line. Let the line reactance between any two of them be X_l and the generator and transformer reactance X_t. At any part of such a string the current fed into the line is made up of the current supplied by the nearest station ($= I_2$), and the sum of the currents supplied by all the rest of the stations behind it ($= I_1$). If the next station in the string supplies a current I_3, when there are an infinite number of stations the condition approached is:—

$$\frac{I_1}{I_2} = \frac{I_1 + I_2}{I_3} = \frac{(I_1 + I_2)X_t}{(I_1 + I_2)X_l + I_2 X_t}$$

from which $$\frac{I_1}{I_2} = \frac{-1 + \sqrt{[1 + 4A]}}{2}$$

where $A = X_t/X_l$.

If X_l is the reactance of 10 miles of line, which is about 4 per cent up to 100 000 kVA, and X_t is the reactance of 50 000 kVA of generating plant and transformers, which is, say, 40 per cent up to 100 000 kVA, then

$$A = \frac{X_t}{X_l} = \frac{40}{4} = 10$$

and with a string of such stations and lines supplying current to a short-circuit the ratio of current supplied by any one station to that supplied by all the other stations more remote from the fault can never exceed

$$\frac{-1 + \sqrt{[1 + 4 \times 10]}}{2} = 2{\cdot}7$$

Distribution of Fault Current Between Conductors.

It is easy to realize that, with a fault on one phase of a 3-phase system, load current may be carried past the

fault by the two sound phases. We shall have occasion further on to consider the effect of this on selective protective gear. It is perhaps less obvious that under certain conditions, with an earth fault on one phase, the two sound phases can carry a current which is solely due to the fault. This cannot happen for faults between phases on any system, nor can it occur for earth faults if the neutral point is insulated from earth, connected to earth through reactances, or earthed at one point only.

On the British grid, however, the transformers connected to the 132-kV lines are star-connected on the higher-voltage side, the neutral point of each of them is earthed solid, and the lower-voltage side is delta-connected. On such a system each transformer, whether connected to generating plant or not, becomes a source of earth-fault current, if one of the phases is earthed anywhere, and, moreover, on such a system the earth-fault current is the cause of currents in the sound

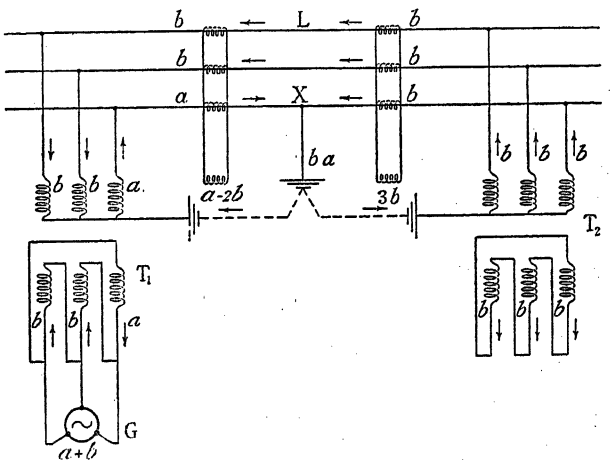


FIG. 5.—Distribution of fault currents between conductors and earth.

phases. This will be clear by reference to Fig. 5 which represents two substations connected to a transmission line L. At the left-hand substation there is a generator G stepping-up through a delta/star transformer T_1 on to the line. The right-hand substation contains a transformer only, and no generating plant. An earth fault is supposed to occur on one of the phases on the line at X. For convenience, the transformers are assumed to have a ratio of 1 to 1. It is obvious that an earth-fault current a will flow in the conductor shown connected to earth. It will pass between the fault and the earthed neutral point of transformer T_1 as shown by the dotted line.

The other two phases of the delta winding of the transformer T_1 form a path for the current generated by the generator G. So long as these phases of the transformer are open-circuited on the star side no current can flow, but a voltage will be induced in the two star windings of transformer T_1, shown not earthed, the voltage in each being due to half the voltage of the generator windings. This voltage is between the earthed neutral and the line, and will cause a current to flow if a closed circuit is provided. The same voltage must appear between the line and the earthed neutral of transformer T_2, which is, therefore, magnetized and able to circulate a current b round its delta winding in the direction shown by the arrows. T_2 thus behaves like a single-phase transformer with a short-circuited secondary. As three delta windings are in series the same current b must flow in each of them; it must also flow in each of the three star windings in the direction shown by the arrows. It follows that an earth current equal to $3b$ flows through the neutral point of transformer T_2, and through each of the phase lines, as shown on the diagram. If the neutral point of transformer T_2 were disconnected from earth there would be no path for the magnetizing current in the star winding and, therefore, no current would flow in the delta. If the delta were open-circuited the transformer would be magnetized, but there would be no path for its current. In either case the current b would disappear. This phenomenon can, therefore, only occur with multiple earthing of the neutral point and transformers having phase coupling, such as star/delta, interconnected-star, or star/star connections with tertiary winding.

Fig. 5 is drawn for two stations only, but any further transformer stations connected to the line L will contribute a certain amount of the a and b type of current, those containing no generating plant contributing type b only to all phases, but those containing generating plant also contributing type a to the faulty phase. How much of the a and b types flow in the system depends on the relative amount and distribution of transforming and generating plant.

As generators or transformers are connected to, or disconnected from, the system, the fault-current conditions are varied; hence the relative distribution of currents, due to an earth fault in the three phases of such a system, is not constant but is dependent on the operating conditions.

EFFECT OF MULTIPLE EARTHING ON THE REACTANCE OF A FAULT CIRCUIT.

If transformer T_2 were switched off on the system shown in Fig. 5, the fault current would be a throughout the circuit. Its path would be through the generator, the line up to the fault at X, and through the return earth path to the neutral point of the transformer. The effect of T_2 is two-fold. In the first place, it reduces the current returning from X to the earthed neutral point of T_1 from a to $(a - 2b)$. The earth return, therefore, absorbs a smaller reactance voltage. In the second place, it introduces the current b in each of the two sound phases in opposition to current a in the faulty phase. This causes the line conductors to act like a current transformer. The two currents b may be said to help along the current a, or, in other words, to reduce the line reactance. For both these reasons the presence of transformer T_2 has the effect of reducing the reactance of the fault circuit.

ANALYSIS OF FAULT CURRENTS INTO LEAKAGE AND BALANCED COMPONENTS.

The fault currents as represented in Fig. 5 do not lend themselves to quantitative treatment of the reactance of the fault circuit, because it is not possible with this

method of presentation to distinguish the different reactances of the loops formed respectively by the earth and the phase-wire return paths. It is, therefore, necessary to adopt an algebraical device in order to represent these currents as composed of two superimposed systems, one of which constitutes purely leakage and the other purely balanced current. A leakage current is one the return path for which is through the earth, whereas a balanced current is one the return path for which is through the sound phase conductors.

It is clear from Fig. 5 that the leakage currents to the right and the left of the fault position X are different, that to the left being $(a - 2b)$, and that to the right being $3b$. In Fig. 6 the analysis of the fault currents through the conductors into these components is given. To the left of the fault position X a leakage current equal to $\frac{1}{3}(a - 2b)$ flows towards X in each of the three conductors, while a balanced current equal to $\frac{2}{3}(a + b)$ flows towards X in the earthed conductor, and half this current flows away from X in each of the sound conductors. To the right of X there is no balanced current, but only a leakage current b in each of the three conductors.

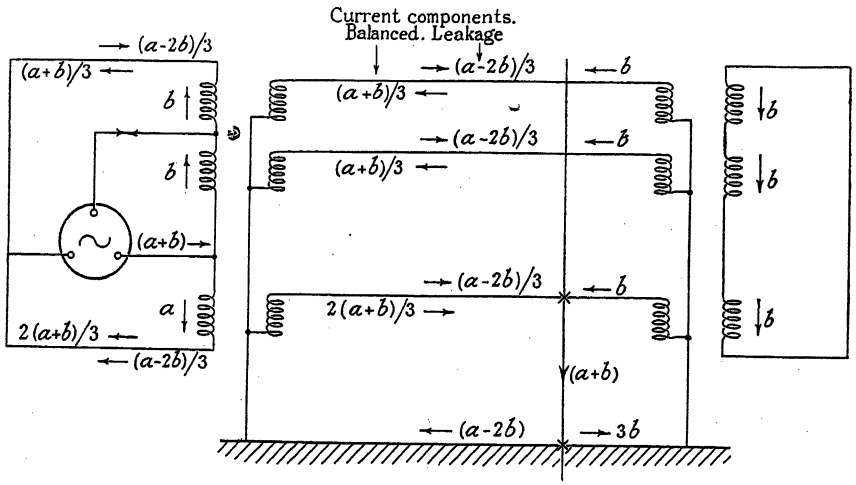


FIG. 6.

The reactance of the various parts of the system to balanced and leakage currents being known, it is possible to calculate the magnitude of these currents where a number of stations are connected to a system. Presentation of superimposed currents in the form given in Fig. 6 would obviously be unduly cumbersome, but the figure can be reduced to a simplified diagram which lends itself to more straightforward and analytical treatment. A description of such a method has been given by one of the authors elsewhere.*

RATIO OF REACTANCES TO BALANCED AND LEAKAGE CURRENTS.

The investigation conducted by the Electrical Research Association and published in the *Journal* as cited above, shows that on the 132-kV British grid lines the reactance to balanced currents is about 0·7 ohm per mile, and that to leakage currents 1·73 ohms per mile for each conductor, or just under 0·6 ohm per mile for the three conductors in parallel, with a common earth return. This figure is based on experiments conducted with comparatively small currents. The possibility must not be excluded that the resistance and reactance of the earth return path may have other values when the earth fault current is as great as several thousand amperes. Positive figures with such currents would be very difficult to obtain. In the absence of such data the ratio for the two currents must be assumed to be approximately 0·85.

The exact figure is, further, somewhat dependent on the nature of the earth return path. The effect of this on the operation of distance protection and the necessary means of avoiding the resultant inaccuracies have been briefly mentioned by one of the authors elsewhere,* but the matter is sufficiently important to demand more detailed presentation. It has been explained above that the impedance loop formed by a leakage current has a very large diameter, which is larger the greater the earth resistance. While, therefore, the impedance to balanced current is a constant figure for any given line, that to leakage current may vary. As mentioned already, the widest variations of possible earth resistivity have fortunately no very great effect, and so the most extreme limits of the ratio of impedance to leakage and impedance to balanced current is likely to be well within the range from 0·7 to 1·0.

The distance type of protective relay has to deal with two superimposed currents, one of which has an impedance of 0·7 ohm per mile and the other an impedance of 1·73 ohms per mile. The resultant impedance depends, therefore, on the relative quantity of each current, and as this varies with the operating conditions the impedance per mile measured by the relay is indeterminate. This indeterminateness is the cause of one of the errors in relay operation mentioned above as influencing the apparent distance of the fault.

The apparent distance is proportional to the ratio of voltage to current fed to the relay. There is only one voltage commonly employed, namely that between the

* C. G. CARROTHERS: *Electrical Review*, 1929, vol. 105, p. 309.

* *Electrical Power Engineer*, 1930, vol. 12, p. 34.

earthed phase and the neutral point. There are, however, three possible sources of current:—

(1) Leakage current obtained from a combination of current transformers, as shown in Fig. 5.
(2) The current in the earthed phase, obtained from a current transformer in that phase only.
(3) A combination of the above two currents.

We have to consider the effect of the choice of each of these alternatives on the apparent distance of the fault.

Relays Operated by Leakage Current.

Fig. 7 shows the possible range of variation of the apparent distance of the fault if the relay is fed by leakage current. The ordinates give the apparent impedance, that is, the ratio of the voltage and current fed to the relay. The abscissæ give the ratio of current in the

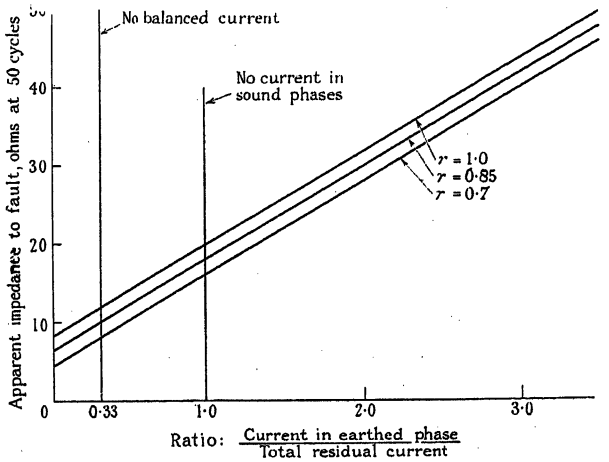


Fig. 7.—Variation in apparent impedance to a fault to earth about 17 miles distant on 132-kV line at relay actuated by total line residual current.

$$\text{Apparent impedance} = \frac{\text{Voltage to earth in earthed phase}}{\text{Total residual current}} = l\left\{\frac{3c + (3r-1)d}{3d}\right\}$$

where l = symmetrical 3-phase impedance,
d = total residual current,
c = current in earthed phase,
r = (Impedance of 3 phases in parallel to single-phase current with earth return) ÷ (Symmetrical 3-phase impedance per phase).

earthed phase to the total residual current, and are, therefore, a measure of the operating condition of the system. It will be seen that, between possible practical limits of operating conditions, the apparent resistance may vary between about 8 and about 48 ohms, for a given fault position. This is a sufficiently wide variation to make it quite impossible to say that the relay behaves in any way at all as an instrument for measuring the fault distance.

The apparent distance is greater, the greater the preponderance of current in the earthed phase. As this is a measure of balanced current we may also say that the apparent distance is greater, the more the proportion of balanced current. This proportion in its turn increases with the amount of generating plant feeding the fault past the relay. The effect of generating plant is, therefore, greatly to slow down the operation of the relay. If the fault is on a section adjacent to a large generating station it is quite possible that the relays at this station will behave as if the fault were well outside the section. If there is little or no generating plant at the station next but one to the fault, or at other stations further back, the relays at this station will behave as if the fault were very much nearer than it really is. Under these circumstances it is not merely probable, but certain, that the wrong relays will operate.

It follows from these considerations that it is not permissible to supply distance relays on systems like the British grid with leakage current alone.

Relays Operated by Current in Earthed Phase.

Fig. 8 shows the apparent impedance for a given fault position when the relays are operated by the current in the earthed phase. The abscissæ give a similar measure to that in Fig. 7, except that the reciprocal is plotted in order that the curves may become straight lines. Here the apparent distance of the fault is more sensitive to

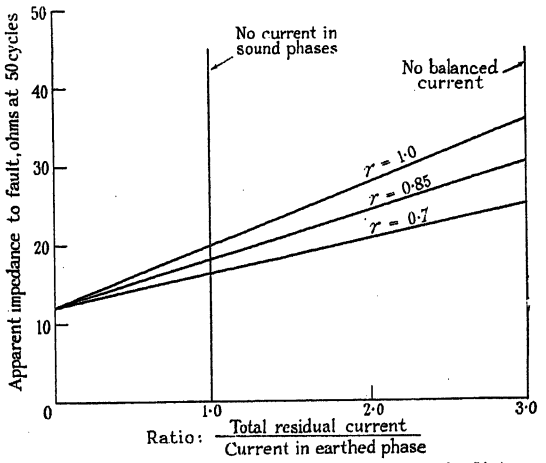


Fig. 8.—Variation in apparent impedance to a fault to earth about 17 miles distant on 132-kV line at relay actuated by current in earthed phase.

$$\text{Apparent impedance} = \frac{\text{Voltage to earth in earthed phase}}{\text{Current in earthed phase}} = l\left\{\frac{3c + (3r-1)d}{3c}\right\}$$

(For explanation of symbols, see Fig. 7.)

the quantity described as r, and is, therefore, more dependent on the earth resistance than in the preceding case. The presence of balanced current reduces the apparent distance of the fault, and, therefore, speeds up the relay operation. The more generating plant there is behind the relay to feed the fault, the quicker will the relay operate. As soon as one end of the section has cleared, the sound phases cease to carry current and the apparent distance of the fault becomes that corresponding to unity for the ratio of residual current in the earthed phase. It may be noted in passing that leakage current and the current in the earthed phase are identical for an open-ended section, and so if leakage current is fed to the relay as in Fig. 7 the same condition is reached as when the current in the earthed phase is fed to it as in Fig. 8 immediately one end of the section has cleared.

The curves in Fig. 8 appear to be as bad as those in

Fig. 7. In practice, however, they give greater stability than their appearance might suggest. The relay on the side where there is a preponderance of generating plant will be speeded up as its operating condition is to the left of the line for which the ratio of currents is unity in Fig. 8. In consequence it may happen that the error revealed by Fig. 8 may actually increase stability. When examples of actual systems are worked out it is found that the encroachment on the stability margin due to the flattening of the relay characteristics is not excessive under most operating conditions. But unfavourable conditions are by no means impossible. A large generating station on a sound section may speed up the relays on this section even more than on the faulty section, and thus cause a false operation. When supplied by the current in the earthed phase only, the relays cannot in any way be described as proper devices for measuring the distance of the fault, or as stable under all the operating conditions that may occur.

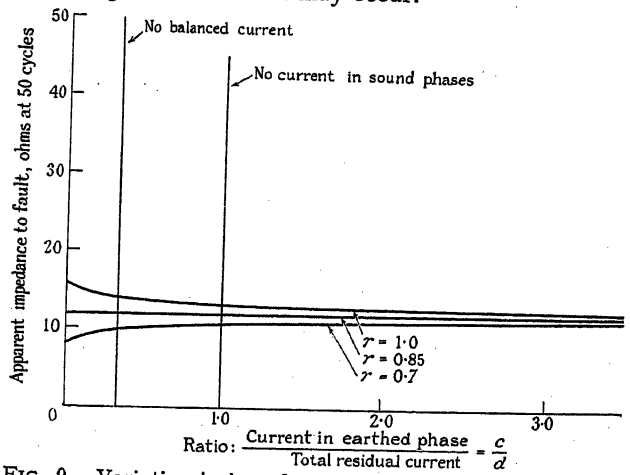


FIG. 9.—Variation in impedance to a fault to earth distant about 17 miles on 132-kV line at relay actuated by compensated current.

$$\text{Apparent impedance} = \frac{\text{Voltage to earth in earthed phase}}{\text{Compensated current}} = l\left\{\frac{3c + (3r-1)d}{3c + 1{\cdot}55d}\right\}$$

(For explanation of symbols, see Fig. 7.)

As this method of working distance relays is reasonably stable, it is being adopted on several parts of the British grid. Calculation shows that the maximum error thus introduced is within the margins allowed, but at the same time this error may possibly be the greatest of all those enumerated in the earlier part of this paper, and its elimination is, if not absolutely necessary, at least very desirable if a high degree of accuracy is aimed at.

Relays Operated by a Combination of Leakage Current and Current in Earthed Phase.

Whereas the presence of balanced current reduces the apparent distance of the fault if leakage current is employed alone, it increases it if the current in the earthed phase is employed alone. From this it may be inferred that the employment of the two currents in the correct proportion will cause these opposite effects to cancel out. The following shows the result obtained by doing this. In the example chosen for the diagram the true distance of the fault corresponds to 12 ohms. It will be seen that with the most probable ratio of the impedance of the system to leakage and balanced currents, namely $r = 0{\cdot}85$, perfect compensation can be achieved, the fault position being entirely independent of the operating conditions on the system. Even if the ratio r varies between the widest possible limits, the error in the apparent fault position is insignificant. This method of combining the balanced and leakage currents has been called "residual compensation" and has been adopted on certain parts of the British grid.

Fig. 10 illustrates diagrammatically how the relays must be connected to give residual compensation. The residual current from the right-hand set of current-transformer secondaries circulates through the primary windings of the three residual current transformers in series. The secondaries of the residual current transformers are connected one to each of the three left-hand current-transformer secondaries to combine with them in supplying current to the relays.

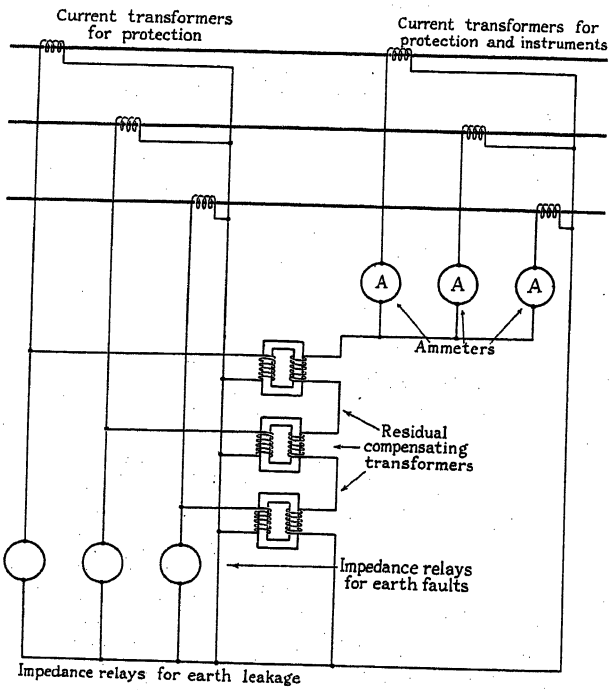


FIG. 10.—Residual compensation for earth-leakage impedance relays.

Calculation of Turns Ratio for Residual Compensation.

The ratios of the residual-current compensating transformers for the 132-kV lines of the Central Electricity Board are calculated as follows:—

Line reactance to symmetrical 3-phase current per mile per phase .. = 0·7 ohm.
Line reactance to residual current per mile per phase .. .. .. = 1·73 ohms.
Line current = residual current + balanced current.
Residual current = 3 (leakage component per phase).

If the balanced current in the faulty phase is I_b, and the leakage current in the faulty phase is I_l, the operating force should be proportional to

$$0{\cdot}7I_b + 1{\cdot}73I_l$$

If q is the compensating transformer ratio, the operating force will be proportional to

$$(I_b + I_l) + 3qI_l$$

or

$$(I_b + I_l)(3q + 1)$$

so that to give the correct operating force

$$3q + 1 = 1{\cdot}73/0{\cdot}7$$

or

$$q = 1{\cdot}03/2{\cdot}1 = 0{\cdot}49$$

Arc Resistance.

A portion of the fault circuit may be an arc. The resistance of this, added vectorially, forms a portion of the total impedance of the fault circuit and makes the apparent distance of the fault greater than the true distance if the protective system is of the impedance type, but not if it is of the reactance type. It is not known at all closely how great is the error due to this cause. There is reason to believe that arc resistance may be great with small currents but that it falls rapidly as the current increases. Its value may depend on many other circumstances, such as whether the arc is struck between horizontal or vertical contacts, or whether it occurs in still air or in a wind. The amount of generating plant sustaining the arc may have an influence, as may also the time during which the arc persists.

The effect of arc resistance is to increase the apparent distance of the fault on all sections. It does not reduce the stability of the system as much as other sources of error may do, which increase the apparent distance on some sections and reduce it on others. Arc resistance would move all points of the relay characteristics on all the sections of Fig. 1(*b*), for instance, by almost the same constant amount to the left, leaving the margins between them not seriously affected. The effect is not quite uniform on all sections, because 1 ohm represents a greater relay time on a short section than on a long one, and so stability is to some extent impaired when sections are of unequal length. Even if the practical effect of a high arc resistance is not that it necessarily makes the protection unreliable, it always increases the clearance time.

Source of Potential.

On systems up to 33 kV, potential transformers are comparatively simple and inexpensive, and it is best to employ these as a source of voltage to the distance relay. For high voltages, however, the cost of potential transformers becomes a serious item. As the relays can operate with very small currents, it is possible to employ potential transformers working on somewhat different principles from those employed for working meters or instruments. Some of these employ the principle of capacitance coupling. They are cheaper and reasonably accurate down to the low voltage which may occur under fault conditions. The cost of such potential couplers can be avoided at the sacrifice of some accuracy if the potential is derived from the lower-voltage side of the power transformers.

There would be no objection to this source of potential if it were truly proportional to that on the line side. If, however, the transformer is helping to feed the fault, and, therefore, stepping up to the line voltage, the potential on the lower-voltage side, reduced to a 1 : 1 transformation ratio, will be higher than that on the line side by the voltage-drop in the transformer. Power will be fed to the fault in all cases if there is generating plant at the stations, and we have seen above that on earth faults transformers with multiple earthing of the neutral point carry fault current even when not connected to generating plant. If uncorrected, a source of voltage derived from the lower-voltage side of the transformers would greatly increase the apparent distance of the fault. It is necessary to subtract from the voltage supplied to the relay an amount proportional to the fault current in

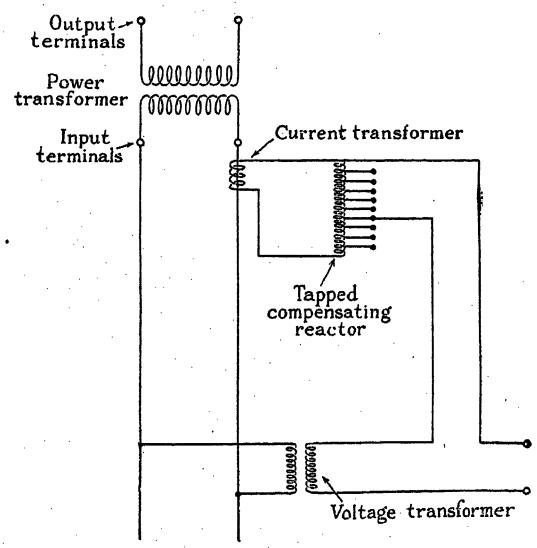


Fig. 11.—Voltage transformer on input side of transformer compensated to give voltage proportional to voltage at output terminals.

the transformer, and, therefore, proportional to its reactive drop. This is done by an auxiliary winding fed through current transformers. The reactance of the transformers varies somewhat with the tapping position. To allow for this is a refinement, as the error under practical operating conditions is not great. It can be done if the compensating circuit contains an impedance with tappings coupled to those on the power transformer, so that as the transformer ratio is varied more or less impedance is inserted in the compensating circuit. The arrangement is shown diagrammatically in Fig. 11. It is not found possible to compensate without a small error. If the error is one of under-compensation, the apparent fault distance is increased. If there is over-compensation the apparent fault distance may with some, but not with all, protective systems, become negative. The relay will behave as if the fault were behind it and will not operate. It is, therefore, essential to under-compensate rather than to over-compensate.

The danger from over-compensation is avoided if connections to the potential element are such that the relay always receives its voltage from the sound phase. The varying ratio of the power transformers also affects the requisite amount of compensation, but the error caused in the apparent distance of the fault by neglecting this is not very great and its practical importance may be ignored without encroaching too much on the stability margin.

The compensation introduces both a ratio and a phase-angle error into the voltage supplied to the relay. The former error is not very great. It is the only one of the two that is important for impedance protection. The phase-angle error is, however, far greater. It affects the accuracy of reactance protection, which for this reason cannot so easily be worked with compensated voltage as an impedance system.

Limitations of Distance Protection.

The cheapness of distance protective systems justifies their employment wherever it is technically possible. This is not, however, by any means equivalent to saying that they are a perfect solution of the problem of selective protection. It has already been seen that the large number of indeterminate factors controlling fault currents limits the length of line that can be safely protected by such systems.

Even where the length of line section and magnitude of the fault currents is such as to make distance protection possible, the disadvantage of the time delay in the clearance of faults remains.

PART 2. PROTECTIVE SYSTEMS DEPENDENT ON DIRECTION OF FAULT CURRENT.

Protection Depending on Directional Relays.

To avoid the drawbacks of long clearance times inherent in distance protection without too great an expenditure in pilot cables, systems have been developed during the last few years which make use of a different specific feature of a faulty section. This is the fact that fault current is fed into such a section at one end and does not leave it at the other. On all these systems operation is effected by means of directional and overload relays, and means are required to compare the positions of the directional relays at each end of the section. Such means demand a channel of communication, which may either be a separate pilot circuit or a channel provided by carrier current over the power lines.

The fundamental idea underlying all such systems is by no means new. It was suggested by Dr. Garrard as long ago as 1908,* but, like many fruitful ideas, it lay dormant for a long period.

Nature of Pilot Circuit.

The essential difference between pilot circuits employed for balanced protection and those employed on systems using directional relays, is that in the former a quantitative comparison of current or voltage must be made by the pilot, whereas in the latter the pilot need only transmit the message, whether a directional relay is in one or the other of two possible positions. This greatly lightens the demand on the pilot wire. An impulse such as a small direct current of the type used in telegraphy will suffice for the transmission of the necessary message. This can be sent over a single wire with earthed return at a voltage no greater than is needed for telegraph purposes. If a pilot wire is used it can, therefore, be lightly insulated and of small cross-section. Its resistance or electrostatic capacitance may be high or low without affecting its serviceableness.

Duplex Protection.

Two protective systems depending on the employment of directional relays and an inexpensive auxiliary circuit have already been described in the *Journal*.* These are known respectively as the "lock-in" and the "interlock" systems.

A third system, known as the "duplex," has not been described before in the *Journal*. It is not the purpose of this paper to describe protective gear but only to discuss the bearing of the circuit conditions on the problem of selective protection. A brief description of fundamental principles will serve this purpose, and as the duplex system has not been described before this may serve to illustrate the points requiring particular attention in the design of any system employing directional relays. The duplex system employs methods well known in telegraph work but less familiar to power engineers. For these latter, a description of the way in which a system originally devised for the transmission of rapid signals can be applied to the totally different purpose of selective protection, may be of interest.

While the signals transmitted by other protective systems employing directional relays are stabilizing impulses confined to the sound sections, the signals transmitted on the duplex system are tripping impulses and are, therefore, transmitted over the channel of communication on the faulty section. This more direct method makes it possible to obtain instantaneous clearance, as with balanced pilot protective systems, whereas those systems employing a stabilizing impulse have to introduce a time-delay of sufficient length to ensure that the stabilizing impulse has taken effect before the tripping relays are allowed to operate.

Development of the Duplex System.

It will be easier to understand the principle of operation if an alternative system which might be considered to be a preliminary stage in the development of duplex protection is described. This is shown in Fig. 12. It employs two pilot circuits instead of the one employed by duplex protection in its present form. The tripping circuit at each station is normally kept open by two pairs of contacts in series with each other. One of the breaks in the tripping circuit is closed by a directional relay at the station itself, and the other is closed when a signal is received over one of the two pilot circuits. This signal is transmitted from the remote station when the directional relay contacts at that station close. Each station, therefore, has, in addition to its directional relay, one relay for transmitting a signal to the remote station

* *Journal I.E.E.*, 1908, vol. 41, p. 588.

* T. W. Ross and H. G. Bell: *Journal I.E.E.*, 1930, vol. 68, p. 801; also H. W. Clothier and B. H. Leeson in the discussion on this paper, p. 827.

and one relay for receiving a signal from that station. Whenever current is fed on to the line from both ends, the directional relays at both ends close their contacts, each thereby causing the second break in the tripping circuit at the remote station also to close its contacts.

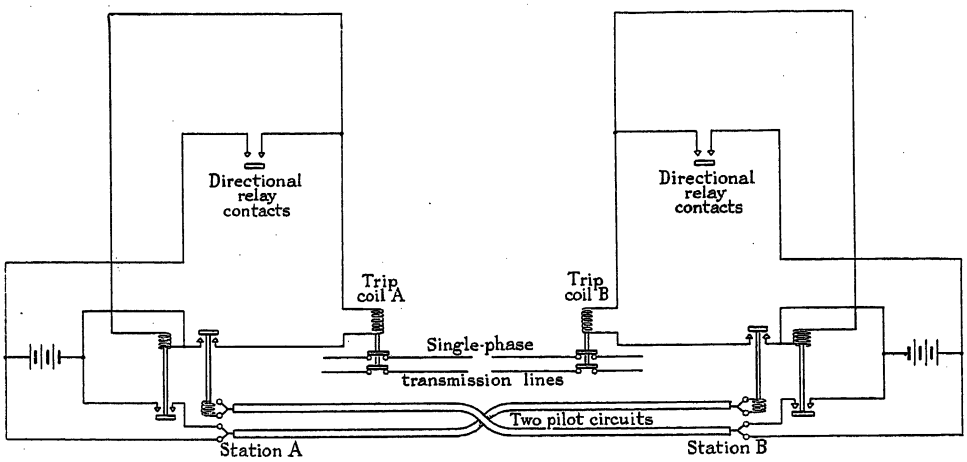


FIG. 12.—Duplex protective apparatus.

The tripping circuit is thereby completed at each end of the section, and the section is cleared.

Protection of a "Dead-Ended" Section.

Apart from the defects arising from the employment of two pilot circuits, this method has another defect, namely, tripping cannot take place unless current is fed from both ends to a fault on the section protected. If, therefore, the section were a "dead-ended" one having no generating plant to feed the fault at one end, it would not be cleared. This difficulty is absent from systems employing a stabilizing impulse, where the failure of a dead-ended section to provide such an impulse is in itself sufficient to ensure clearance. How this difficulty is overcome with the duplex system will be seen in Fig. 13. In this figure the directional relay contacts "y" and "y'" are normally bypassed by overload relays "x" and "x'" which open with excess current. At the "dead-ended" section there is no current to operate the relays "x" or "x'." Supposing that station B is the dead-ended one, there is no current to open the contacts of relay "x'" or to close those of "y'." The tripping circuit contains only one break, and the trip coil is energized as soon as the signal is received from station A. This signal closes the contacts "p'." If this signal were received whenever the directional relay contacts "y" closed, the station B would be cleared with the ordinary load current fed to the section. It is therefore necessary to ensure that relay "p'" at station B can only be energized when the current fed from station A on to the section is a fault current; that is, in excess of the load current. To ensure this, relay "z" is introduced into the circuit, energizing the relay and sending a signal over the pilot. This is an overload relay which closes its contacts with overload. Any system depending on the successive operation of relays must be so designed that the sequence of operations is positively determined. For instance, on a growing fault or where the fault current is near the setting of the over-

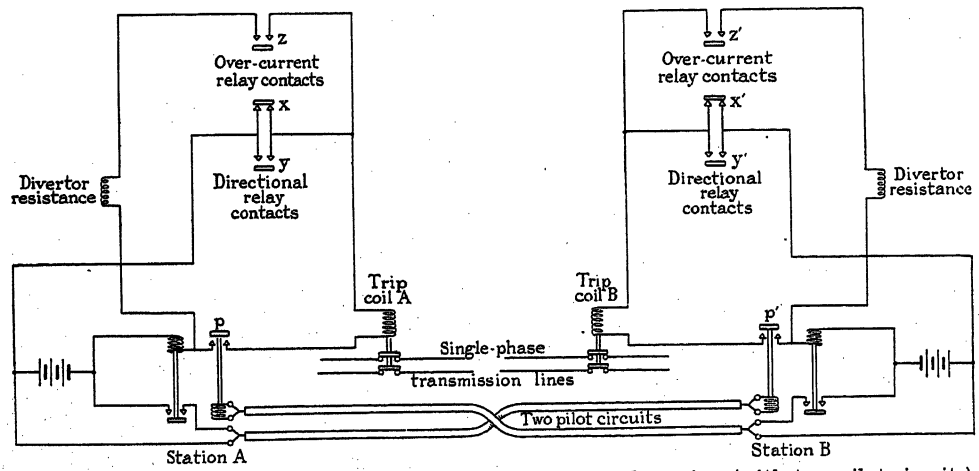


FIG. 13.—Duplex protective apparatus on section of single-phase ring (with two pilot circuits). Adapted for dead-end operation.

load relays, the danger that the operating relay may work a little more readily than the stabilizing relay and lead to a false operation has to be avoided. This contingency is made impossible by giving the "z" relays a higher setting than the "x" relays.

The closing of contacts "p'" at station B completes the circuit through the coil, energizing the relay at B which sends its tripping impulse to station A, and it therefore causes relay "p" at station A to close its contacts and cause tripping there.

If station B can feed fault current, the relay contacts "x'" open and "y'" and "z'" close, and tripping occurs at both stations simultaneously. If station B cannot feed fault current, the relay contacts "x'" remain closed but "y'" and "z'" remain open. Station B is cleared immediately and station A thereupon clears in quick succession.

bottom half of the differential relay is energized from the local battery, but an alternative path for the current from this local battery is provided through the upper half of the differential relay in the opposite direction, through the pilot wire and through the upper winding of the differential relay at the remote station. As the current divides equally in opposite directions through the local differential relay, this is not energized. The current flows in one direction only through the remote differential relay and energizes this. In that way the differential relay at the remote station receives a signal to close its contacts, while the current through the same pilot does not close those at the near station. If, however, at both stations A and B the sending relays are energized, the battery voltages are in opposition through the circuits completed through the upper portion of the differential relays, whilst at each station a local circuit

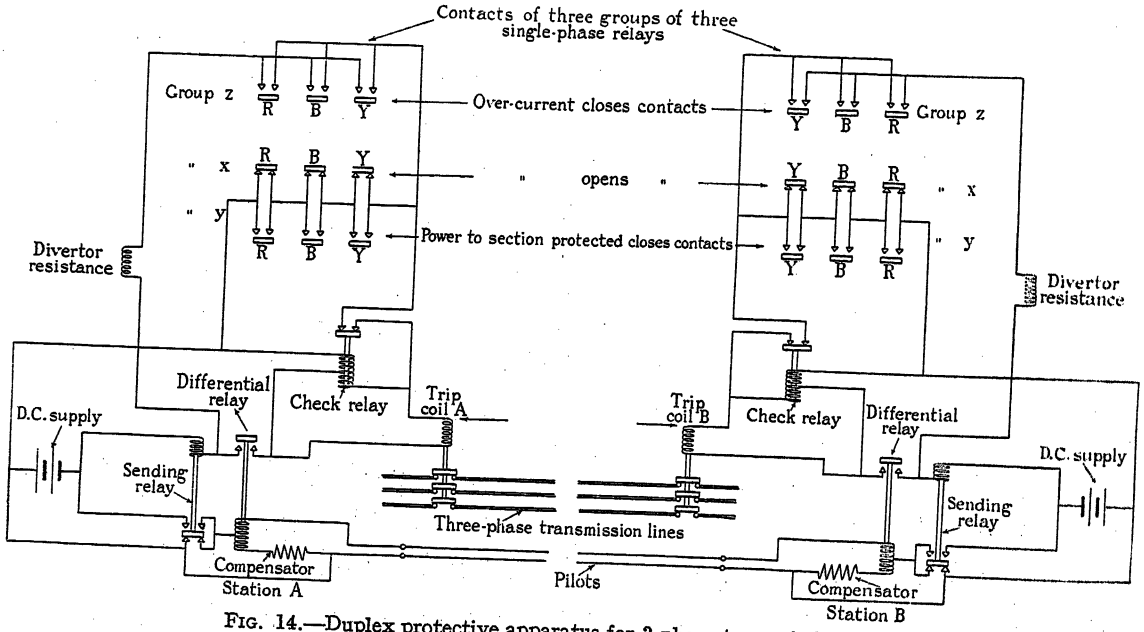


FIG. 14.—Duplex protective apparatus for 3-phase transmission line.

The divertor resistance shown in Fig. 13 is necessary to ensure that sufficient operating current flows through the trip coil, as otherwise this would be short-circuited through the relay "z."

The Duplex Principle.

Fig. 14 shows further modifications necessary (1) in order to employ a single pilot circuit of such a nature that its vulnerability does not jeopardize the reliability of the system, and (2) in order to apply the system to a 3-phase transmission line.

The first requirement is met by employing over the pilot wire a signalling system such that signals can be sent simultaneously in opposite directions over the same circuit. As long as the sending-relay operating coil is not energized, the contacts remain in their lower position. In this position the bottom half of the differential relay, which is also the receiving relay for a signal from the distant station, is short-circuited. If the sending relay is energized and its contacts are in the upper position, the is completed through the lower portion of the differential relay. Under these conditions each differential relay closes its contacts.

The purpose of the compensator is to introduce a sufficient resistance into the path through the bottom portion of the differential relay, to ensure that the current through the two portions will divide equally as long as no signal is being received from the far end.

This circuit is identical with that employed for duplex telegraphy, where telegraph signals are sent in opposite directions over the same circuit at the same time without interfering with each other. The experience gained with the application of this circuit throughout the world for such a long period is, therefore, available and ensures the reliability of this portion of the system.

EFFECT OF SEVERANCE OF PILOT WIRE.

It is obvious that in systems using stabilizing impulses severance of the pilot, if confined to the section carrying the fault, cannot prevent proper operation of

the gear. The same is true of the duplex system, as at the moment when signals are being transmitted in opposite directions over such a system the pilot circuit itself is carrying no current. If the pilot circuit is severed at that time, the correct operation of the protective device will take place just as if the pilot were there.

If the pilot is severed and there is no fault, the sending relays at both ends are not energized and again the pilot carries no current. Therefore no false operation can occur owing to severance of the pilot. Should, however, the pilot wire be severed on a sound section at the time when a fault occurs on another part of the system, there is the possibility that the sending relay at one end of the section having a severed pilot would be energized and cause tripping at that station.

The contingency that a pilot is severed at the same time as a fault occurs elsewhere is very remote if the pilot is inspected at reasonable intervals. In this remote contingency the only drawback is incorrect tripping of one section only. The remote possibility of a severed pilot wire causing a false operation, and the comparatively small amount of trouble occasioned by such a contingency, justify the adoption of a more vulnerable form of pilot cable than is permissible with protective systems on the balanced-current principle.

Pilot Earth-Wire.

The auxiliary circuit which appears both technically and economically to be the most promising, is a copper

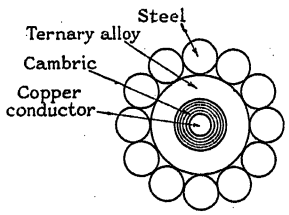


Fig. 15.—Section of pilot earth-wire (twice full size).

wire embedded in the earth wire with the earth as return path for the d.c. signal. Exhaustive and prolonged tests with different types of such pilot earth-wires have shown that the most suitable design is that illustrated in Fig. 15. It consists of a soft, annealed, cambric-insulated copper conductor lead-covered and surrounded by the steel stranding of the earth wire.

Early experiments showed that it is very important to maintain an absolutely uniform diameter over the lead and for the galvanized-steel wires to be wound very tightly round it. If this is not done the earth wire will stretch after erection. The maximum stretch of a properly-constructed pilot earth-wire can be limited to 0·03 per cent after stringing, and this is too small to have any material effect on the sag.

Effect of Current Fed Past the Fault.

When applying to a 3-phase system any protective system employing directional relays, a difficulty is introduced by the uncertainty as to the distribution and direction of currents in the three phases. It is quite possible that on any section of the transmission system on the occurrence of a fault, current may be in one direction on the faulty phase or phases and in the opposite direction on the sound phase or phases. If, therefore, a single-phase directional relay is introduced into each of the phases and each of these is able to transmit a tripping or stabilizing signal to the remote station, it is certain that a number of incorrect signals will be transmitted all over the network.

With duplex protection this would result in a whole group of false operations, and with systems employing stabilizing impulses it would prevent clearance of the fault.

If a 3-phase directional relay is employed, there is less certainty of incorrect operation or failure to clear. Such a 3-phase relay would operate by the difference between the fault current, which is always fed in the direction of the fault, and any currents which might be fed away from the fault. As a general rule, the preponderating current is in the direction of the fault, but it is found by calculation that this is not necessarily the case on every line. Even when it is the case, the operating force on the directional relay is reduced by any currents in the sound phases fed away from the fault, and its operation is thereby rendered more uncertain when the voltage is very low, as it is bound to be during the fault.

In a recent development of the "lock-in" system this difficulty is overcome by the employment of a 4-element directional relay. Three of the elements react to the direction of power between phases, and the fourth to the direction of power to earth. The latter is designed to be far more powerful than the other three, so that it may overcome the effect of any power in the phase wires fed past the fault.

The interlock and duplex systems employ for the same purpose single-phase directional relays only, so connected that the directional relays on the sound phases are rendered inoperative and those on the faulty phase take charge. The solution employed in the duplex system is embodied in Fig. 14 and will serve to illustrate how this purpose may be achieved.

The principle underlying this method of employing directional and overload relays is that any current greater than the normal load current is invariably fed towards the fault. On any phase on which such a current occurs the overload of the "x" group will open, and it will depend on the direction of the current whether or not the corresponding directional relay in group "y" closes its contacts. The necessary circuit to indicate a fault in the direction of the protected section can only be made, therefore, if fault current is fed in the faulty phase in the requisite direction. The groups of relays "x" and "y" function as phase-selecting relays.

The "z" group of coils are all connected in parallel, as it is possible that the overload may be on one phase only and it is essential that on whichever phase it occurs the station shall send the necessary signal to the remote station if its directional relays are set to send such a signal.

Effect of Reversal of Current.

On a ring main it is possible that the current in a given section may reverse as soon as a fault is cleared,

because during the fault the direction of current will be towards the fault, but after clearance the direction will be that of the load current and may be opposite to the direction of the fault. In such a case the directional relays at both ends of the sound section will alter their positions as soon as the fault is cleared. If those at one end close to indicate flow of power towards the section before those at the other end have opened to indicate flow of power away from the section, there is a risk that such a section may clear. To avoid this the check relay shown in Fig. 14 is introduced.

As long as the relays at the station are set to trip, i.e. as long as there is a circuit through groups "x" or "y," and the differential relay is closed, the battery current through the check-relay energizing coil passes in opposite directions through the upper and lower halves and therefore does not energize this relay. If, however, a tripping signal is received from the remote station, causing the differential-relay contacts to close while the circuit is broken through the relay groups "x" and "y," only the upper portion of the check-relay winding is energized. This is opened, introducing, therefore, a further source of stability in the tripping circuit. This check relay is so connected that in opening it cuts off the battery from its lower half and is therefore not able to reclose until the differential relay reopens its contacts.

PART 3. EMPLOYMENT OF THE SYMMETRICAL COMPONENTS OF CURRENT AND VOLTAGE IN THE LINE.

Voltage Supply to Directional Relays.

The most usual form of directional relay operates under the combined action of its current and voltage coils, which are supplied from current and voltage transformers in circuit with the protected feeder. For correct operation there must be a sufficiently large component of the voltage in phase with the current. This cannot be ensured invariably. During a fault the voltage on the phase or phases carrying the fault current may be too low to ensure operation, and even when there is ample voltage available its direction may not be such as to give the requisite component to operate the relay. The most advantageous method of making the current and voltage connections has been completely analysed by Mr. G. E. Taylor.* He shows that under the most favourable conditions an element of uncertainty remains due to the impossibility of predicting the phase relationship between the currents carried by the current and voltage windings of the relays under all types of short-circuits.

Distortion of Vector Diagram.

This is because during a fault the three phases are neither equal nor displaced at 120° to each other as they are during normal operation on balanced load. The nearer the fault, the greater is the collapse of voltage on the faulty phase or phases, and the greater the distortion from symmetry of the voltage diagram. Except for a symmetrical 3-phase fault, the distortion is not accompanied by a proportional reduction in the size of the vector diagram representing the voltage. There is plenty of voltage left, only it is not necessarily in the right direction to ensure correct relay operation, if the most usual method of connection is retained. As distortion of the vector diagram is a characteristic of a fault, and is moreover the more pronounced the nearer the fault, it can be employed as a means of operating the protective relays. They must be arranged to respond to something which is a measure of the distortion. To some extent the voltage-drop is such a measure, though a very imperfect one. The difference between this quantity (the voltage-drop) and the normal voltage is used in distance protection when the voltage remaining after deducting the voltage-drop supplies a restraining force which is less the nearer the fault. For the satisfactory operation of directional relays it is desirable to find a measure which will be the greater the nearer the fault. That would be given by an operating force which depends directly on the departure of the distorted vector diagram from a symmetrical 3-phase diagram.

Analysis of Vector Diagram into its Symmetrical Components.

Mr. C. Le Geyt Fortescue* has given a means of expressing this departure in convenient terms. He has shown that any unsymmetrical 3-phase diagram can be represented as the superposition of three symmetrical systems:—

(1) A symmetrical 3-phase system of forward phase rotation, known as the positive phase-sequence components.
(2) A symmetrical 3-phase system of reverse phase rotation, known as the negative phase-sequence components.
(3) A single-phase system consisting of equal and equi-directional currents in each of the three conductors, known as the zero phase-sequence components.

The first of these systems is the only one present during normal operation on balanced load. The magnitude of the vectors of the other two systems is a measure of the distortion due to the fault currents.

Employment of Zero Phase-Sequence Components.

On earth faults the zero phase-sequence component is present and constitutes the whole of the earth-fault current. It is the direct and only cause of the displacement of the neutral point of the voltage diagram. This displacement vector is large and its direction determinate. It is either in phase or 180° out of phase with the zero phase-sequence current, according to the direction of the fault. The zero phase-sequence, variously described as "spillover," "residual," or "leakage current," is an ideal supply to protective relays and is used in many forms of earth-leakage protection. It can also very readily be used for directional protection. Where a power transformer with earthed neutral is available, the relays may be supplied from current transformers in the neutral connection. If, as on the British grid, the neutral points of the power transformers are earthed at all stations, the neutral earth current is considerably greater at stations adjoining the fault than at more

* G. E. Taylor: "Reverse-Power Alternating-Current Relays for Three-phase Generator and Feeder Protection," *Journal I.E.E.*, 1928, vol. 66, p. 1148.

* *Transactions of the American I.E.E.*, 1918, vol. 37, p. 1027.

remote stations, on account of the greater displacement of the neutral of the voltage diagram. The directional relays, therefore, receive the greatest operating force where they need it most. If there are no power transformers with earthed neutral points, the directional relays may obtain a supply proportional to the zero phase-sequence voltage or neutral displacement from a potential transformer with earthed neutral and an interconnected-star or auxiliary delta winding. Whether derived from a power or a potential transformer, the neutral earth current is a measure of the zero phase-sequence voltage, while the earth leakage current is proportional to the zero phase-sequence current in both direction and magnitude.

Employment of Negative Phase-Sequence Components.

On faults between phases there is no zero phase-sequence component. The distortion is entirely due to the negative phase-sequence component. The nearer to the fault, the greater this is. It may appear surpris-

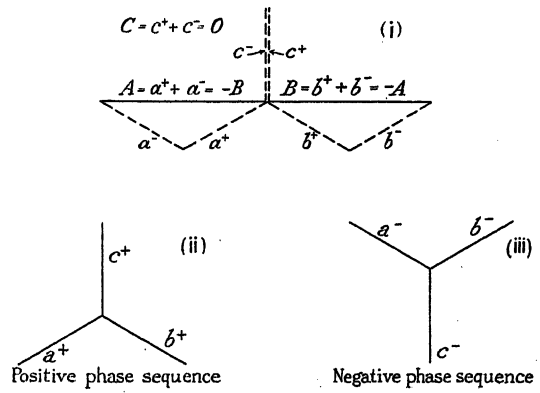


FIG. 16.—Example of resolution of asymmetrical 3-phase current into balanced 3-phase components.

(i) Three-phase circuit with equal and opposite current in phases A and B, and zero current in phase C.
(ii) and (iii) Analysis of currents in (i) into symmetrical components of current.

ing that the purely single-phase current appearing on a fault between phases may be represented as consisting of two 3-phase currents. Fig. 16 shows the reason for this. The fault is between phases "a" and "b." The current in each of these conductors is seen to be the resultant of two currents making an angle of 60° with each other, while the currents in the conductor are seen to be equal and opposite and thus to cancel out.

Negative phase-sequence components are to faults between phases what the zero components are to earth faults, although it should be noted that under earth-fault conditions there is always a negative phase-sequence component present. The negative phase-sequence components offer the obvious source of supply to directional relays for phase-to-phase faults. It seems regrettable that they are not more extensively used. There are many possible ways of connecting the relays to the instrument transformers so that they may respond only to these components. These methods all require circuits containing resistance and inductance. Some circuits contain capacitance as well. The basic principle of them all is simple.

It is always possible to design a 3-phase network that will contain two equipotential points if a symmetrical 3-phase voltage is applied, and where the same two points will not be equipotential if the direction of rotation

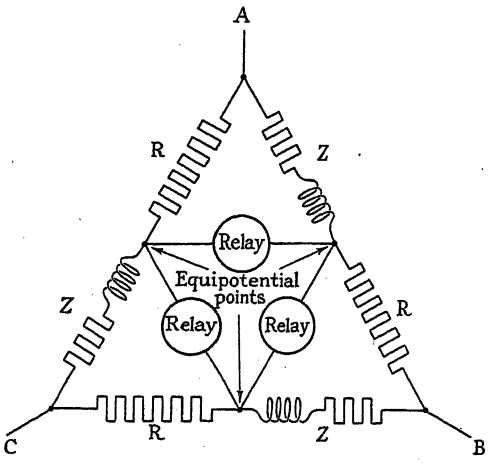


FIG. 17.—Network containing 3 equipotential points with symmetrical 3-phase current supplied to points A, B, and C, with negative phase rotation.

of the applied voltage is reversed. A relay connected across such points will, therefore, carry a current proportional to that in the reversed system.

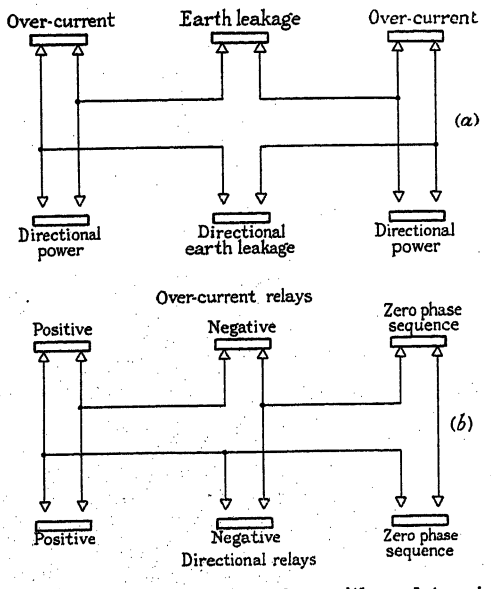


FIG. 18.—Duplex protective relays with predetermined order of precedence.

(a) Overload and earth leakage.
(b) Asymmetrical components.

Fig. 17 shows one of the many possible methods of connection. This particular one was described* by R. Dubusc, who has contributed largely to the employment of the negative phase-sequence components for protection.

* *Revue Générale de l'Électricité*, 1927, vol. 22, p. 298.

Directional Protection.

By an elaboration of the method of connecting the "x" and "y" groups of relays shown in Fig. 14, the protective system may on occasion be restricted automatically to relays operating under one or other of the symmetrical components of current in the line.

Fig. 18(*a*) shows a combination of directional and overload phase-selecting relays in which the middle pair is designed to take complete control of the circuit, irrespective of the action or non-action of the outer two.

Generally, the outer two would be operated by ordinary single-phase over-current and directional relays, and the middle pair by residual current and directional residual current. If a residual current enters the section protected, the upper contacts are broken and the lower contacts close and bridge across the other two, thereby bypassing them. If the leakage is in the opposite direction the circuit is kept open by the upper contacts.

As a further elaboration, a group of three relays can be given a definite order of precedence up to any number. Fig. 18(*b*) shows three pairs designed to operate on residual current first, negative phase-sequence current second, and positive phase-sequence current third.

[The discussion on this paper will be found on page 721.]

SOME NOTES ON OIL CIRCUIT-BREAKER DESIGN AND PERFORMANCE.

By HERBERT PEARCE, B.Sc.(Eng.), Member, and T. T. EVANS, Associate Member.

(*Paper first received* 13*th October, and in final form* 30*th December*, 1931; *read before* THE INSTITUTION 17*th March, and before the* NORTH-WESTERN CENTRE 15*th March*, 1932.)

SUMMARY.

The principal cause of inconsistency in the short-circuit performance of oil circuit-breakers is considered to be the erratic movement of the oil. Quick-break circuit-breakers are advantageous for the higher voltages, and still further improved performance and consistency is obtained by the use of suitably-designed contact shrouds. Reference is made to published tests on some of the recent designs. The principal features of design affecting arc rupture are briefly reviewed and are followed by notes on the causes and effects of the magnitude and the rate of rise of recovery voltage.

The importance of short-circuit testing is emphasized, and a plea is made for facilities for testing on site. A description of short-circuit testing arrangements is given, including a detailed description of the oscillograph equipment; also general notes on the calculation of 3-phase kVA. Reports are included of recent short-circuit tests carried out on oil circuit-breakers fitted with a new type of shrouded contact.

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(1) INTRODUCTION.

The oil circuit-breaker was introduced at a time when the gradual use of higher and higher voltages rendered it increasingly difficult to confine in a reasonable space the arc obtained from the air circuit-breakers of those days. The higher insulation value of oil enables the permissible break to be reduced and, within the capacity of the breaker, avoids external arc or flame. These two factors ensured the popularity of the oil circuit-breaker.

The concentration of power plant and the extensive interconnection of supply systems necessitated close investigation into the operation of oil circuit-breakers under fault conditions, and active study of the conditions surrounding the rupture of an arc, but the subject proved very complex, and progress was slow. Still the art progressed surely, as any art must when it is actively pursued in the leading countries of the world.

Apart from increasing the mechanical strength of breakers, improvements in design were made with the object of reducing the arc energy, arcing time, and overall switching time. These improvements were, in the main, concentrated on the design of contacts in order to obtain increased thermal capacity, more efficient contact when passing large currents, and a quick-break opening action. Research is being continued actively to make more efficient use of the material available, and lately much attention has been paid to the phenomena accompanying the interruption of high-power arcs, both in air and in oil, and this has led to a marked improve-

ment in performance obtained by the introduction of certain novel features.

The essential problem is to separate two (or more) metal contacts and to fill the intervening space with a good insulating medium as quickly and as consistently as possible. Why is the action so inconsistent and what are the principal factors that determine success or failure?

Inconsistency of Action.

It has often been suggested that the oil itself is the principal cause of inconsistency. As the contacts separate, an arc is formed which breaks up a portion of the oil into its constituent gases. A detailed analysis of the physical changes and the energy balance-sheet involved has been given by C. E. R. Bruce.* The production of the arc bubble sets up a sudden hydrostatic pressure which is transmitted in all directions. Thus in a 3-pole double-break oil circuit-breaker of the conventional type having a common tank, there are during the arcing period six arc bubbles producing pulsating hydrostatic pressures which are not only of different phase, but are reflected irregularly from the various surfaces of the tank and obstructed unequally by one another and by other obstructions in the tank. It is difficult to conceive the possibility of a regular and consistent movement of oil under such conditions, particularly since there has to be provided an air expansion chamber as one boundary of the oil. Thus it is no longer a wonder why a simple oil circuit-breaker is so inconsistent in its behaviour, but rather a matter of surprise that its performance should not show greater divergence.

It is proposed to review briefly and in simple terms the physical action in an arc, to compare some of the more recent types of circuit breakers with those of the conventional pattern, to consider certain features of construction and of operation that affect the behaviour of the circuit breaker, to review some of the aspects of short-circuit testing, and finally to give the results obtained from short-circuit tests on one of the new types of circuit breakers.

It is only possible to refer briefly to many of these features and to describe some of the recent designs, particularly those on which the authors have personal knowledge and those of which data have been published. It is realized that this cannot cover adequately the whole field of oil circuit-breakers, but it is hoped that even a general and necessarily incomplete review of this nature may stimulate discussions of the problems, and also lead to some definite action which may be of mutual advantage to the whole industry.

(2) Phenomena in an A.C. Arc in Oil.

The arc is explained as a stream of positive and negative ions passing between electrodes in a gaseous space. The stream of ions is maintained by the potential gradient across the contact gap. Within this space there is a production of ions by emission from the hot electrodes and by collision, and a loss of ions due to recombination and dispersion. The arc will be maintained so long as the production of ions is greater than the recombination. In this paper the a.c. arc only is being considered, and the arc phenomena will be periodic. The natural passage of the current through zero forces a periodic arc extinction of twice the frequency of the a.c. current. With the current approaching its passage through zero the rate of production of ions is decreasing to a minimum at the instant of current zero. At some instant before current zero the rate of recombination of ions may become equal to the rate of production and thereafter exceed it. From this instant the mixture of gas and metal vapour in the contact gap must become less conductive and attain increasing electric strength. The potential gradient building up across the contact gap, due to the recovery voltage across the circuit-breaker terminals, will increase the production of ions and may, together with thermal ionization in the still hot gases, be responsible for a higher rate of production than the rate of recombination, thereby leading to a re-establishment of the arc until the next passage through zero current. When the rate of recombination is sufficient to produce, in the available short interval of time, an electric strength of the contact gap that will withstand the maximum potential gradient applied, then arc rupture will be complete. The action has been aptly described as a race between the building-up of the insulation and the recovery voltage.

It is evident that the aim should be to facilitate recombination and dispersion and if possible limit the production of ions, due particularly to thermal ionization in the gases, at the instant of zero current. Recombination and dispersion of ions can be facilitated by turbulence of the arc gases, and by intermixing with the surrounding cold oil. A limitation of the production of ions may be effected by rapid cooling of the arc gases, thereby reducing the chance of self-ionization of the gases due to high gas temperatures.

The quantity of gas generated increases with increasing arc energy. The increase is not solely determined by the arc energy, as the contact design and other physical details may have appreciable effect on the gas generation. Some relation exists, however, between the quantity of gas, the rate of generation, and the consequent mechanical stress of the circuit breaker.

(3) Different Types of Oil Circuit-Breakers.

The development of the oil circuit-breaker since its early days has brought about many changes in design. In order to deal with the fundamental features of present-day practice, it is convenient to consider three classes of breakers, according to the type of contact used:—(*a*) The plain break; (*b*) the quick break; and (*c*) the shrouded contact.

In each of these classes a multitude of designs is possible. A discussion of design detail will, however, only be entered into where this materially affects the phenomena of arc rupture.

(a) The Plain-break Circuit-breaker.

A plain-break circuit-breaker is characterized by its straightforward design. No device is incorporated whereby the contact speed of the moving contact may be made different from the cross-bar speed. The contact assembly is directly exposed to the whole of the oil in

* *Journal I.E.E.*, 1931, vol. 69, p. 557.

the tank or tank section without any intervening barrier or shroud. There is seldom any serious attempt in the contact design to increase turbulence more than is natural to a gas globe generated under the specific conditions inherent to a particular design. Discontinuity of the arc is brought about purely by elongation of the arc gap, both by the opening movement and by the natural magnetic blow-out.

(*b*) *The Quick-break Circuit-breaker.*

The term "quick break" is here used to describe designs in which the arcing or auxiliary contacts remain in contact for half or more of the total break of the main contacts. A hammer blow or similar action causes their release. The speed of the arcing contacts is usually between 20 and 25 ft. per sec.

The quick-break contact can be regarded as an attempt to reduce the time component of the arc energy; it is not correct to assume a proportional reduction in the arc energy. The improvement obtained is more marked at the higher voltages.

(*c*) *Breakers with Shrouded Contacts.*

The value of enclosing the contacts of an oil circuit-breaker in a shroud has been recognized by many designers for a number of years. The primary advantage is a reduction of the arcing time. It is also expected to reduce to a very marked extent the possible stresses set up in the circuit breaker. The most familiar form of shrouded contact is the explosion pot, and this has been used extensively for many years. More recently other devices have been introduced to achieve similar objects.

(i) *The De-ion Grid Oil Circuit-breaker.*—The theory and construction of the de-ion grid oil circuit-breaker* have been fully described by Slepian,† and Baker and Wilcox.‡

As indicated in Fig. 1, the fixed contacts are enclosed in a special shroud consisting of horseshoe plates of insulating material interspersed at intervals with similarly-shaped iron plates that are insulated from contact with the arc. The moving contact breaks within a narrow slot formed by the shroud. Since this slot is closed on the outer side a certain quantity of oil is trapped between the arc and the slot wall when the breaker opens under load. The principle underlying this construction is that of maintaining the arc in close contact with the trapped oil by the natural blow-out assisted by the local interaction between the arc magnetic field and that induced in the iron plates. This oil is vaporized by the arc, and the only means of escape for the gas produced is through the arc itself. The turbulence produced by the continuous introduction of relatively cool non-ionized gases into the arc as it travels outwards, causes, at zero point in the current flow, a very rapid increase of the electric strength of the arc path by a de-ionizing action on the arc gases. This action is assisted by similar non-ionized gases projected into the arc from oil absorbed in the edges of the insulating plates subjected to the heat of the arc.

(ii) *The Quenched-Arc Circuit-breaker.*—In this form of circuit breaker, described by L. C. Grant,* the shroud (as shown in Fig. 2) consists of a number of thick annular metal discs suitably spaced and secured to the fixed contact. The moving contact takes the form of a vertical rod passing through a central hole. It was suggested that, as the arc is drawn out, it is forced into the spaces between the discs and so divided into a number of shorter arcs that travel towards the outer edge of the disc. The continuous movement of the arc and the comparatively large thermal capacity of the discs tend to produce relatively cool cathode conditions in the arcs, and so some advantage is claimed in inter-

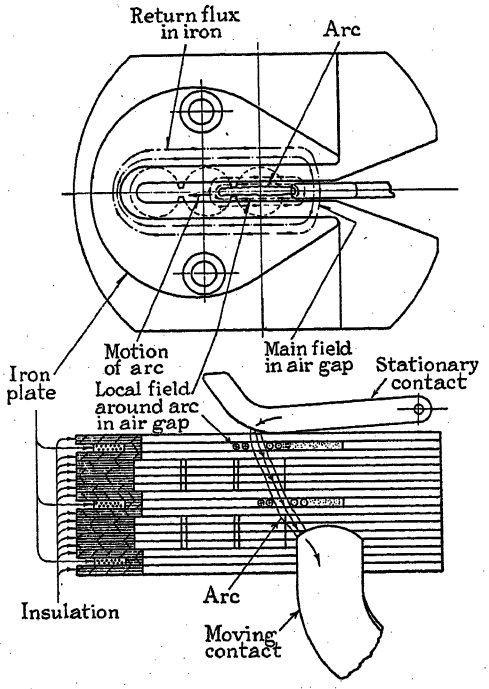


FIG. 1.—De-ion grid.

ruption of the current due to the de-ionization of the arc gases when the arc current passes the zero point of the current wave.

(iii) *The Oil-Blast Circuit-breaker.*—In this circuit breaker, described by D. C. Prince and W. F. Skeats,† the shroud consists of a conventional explosion-pot containing contacts so arranged that a blast of oil is passed across the path of the arc.

As shown in Fig. 3, the fixed contact is resiliently mounted, and just below it is arranged a floating contact.

The moving contact is a hollow rod with holes in the lower walls to allow a flow of oil into and out of the explosion pot. When the breaker is closed the floating contact is trapped between the two main contacts. As the breaker opens, the floating and moving contacts move together during the first part of the stroke, and a short arc is drawn between the fixed and floating

* The construction and action of this circuit breaker should not be confused with those of the de-ion air circuit-breaker, in which the arc is caused to split up into several small arcs in series and move rapidly over the surface of a number of metal plates until the moment of current zero, when the de-ionization of the air films prevents the re-establishment of the arc.

† *Transactions of the American I.E.E.*, 1930, vol. 49, p. 421.

‡ *Ibid.*, 1930, vol. 49, p. 431.

* *Journal I.E.E.*, 1930, vol. 68, p. 1089.

† *Transactions of the American I.E.E.*, 1931, vol. 50, p. 506.

contacts. This arc forms gases in the explosion chamber, and the oil therein is placed under compression. The pressure cannot be relieved until the floating and moving contacts part company at the limit of travel of the former contact. A second arc is then drawn between these members, and at the same time oil and gases are forced down the hollow rod and out into the tank. As soon as a zero point in the current wave is reached, the arc gases are swept out through the hollow contact by a blast of clean oil, thus introducing a high electric strength into the path of the arc and effectually preventing its re-establishment.

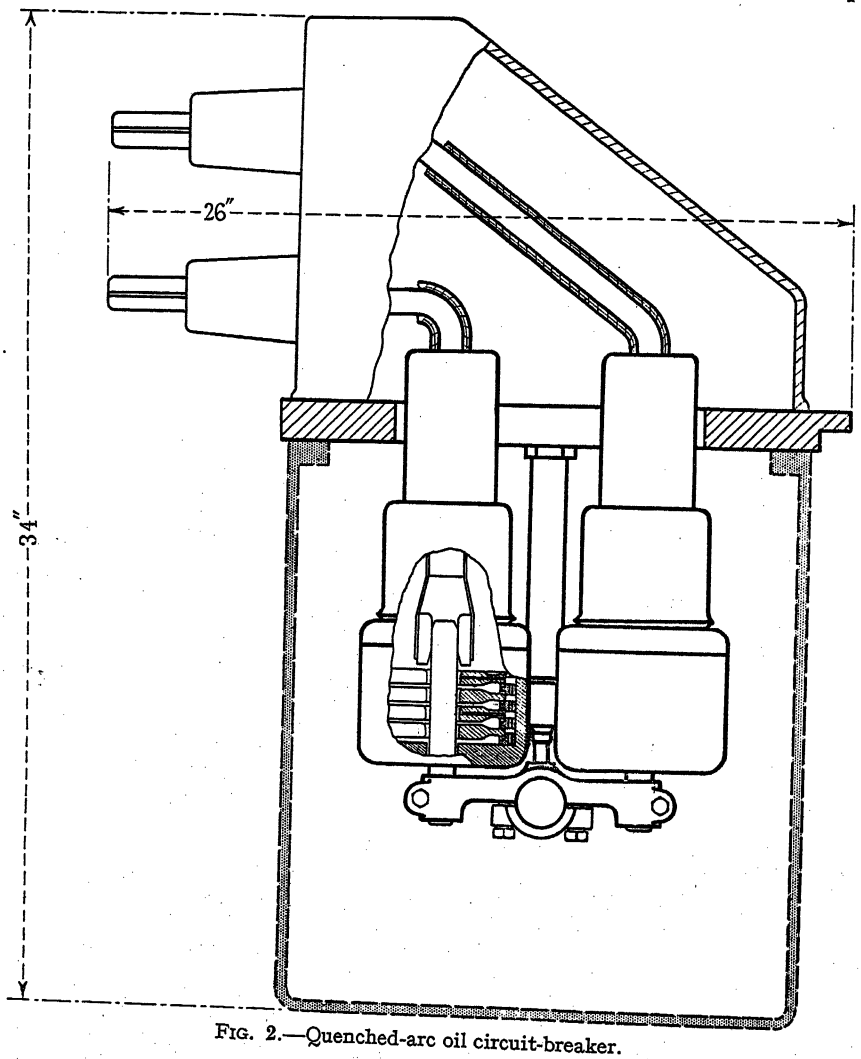


FIG. 2.—Quenched-arc oil circuit-breaker.

(iv) *The Impulse Circuit-breaker.*—A natural development of the oil-blast circuit-breaker has been the provision of external means for producing a blast of oil entirely independent of the arc current. This arrangement has become known as the impulse circuit-breaker, and a series of tests on it were made by D. C. Prince and E. J. Poitras.* These tests were carried out on a circuit breaker in which the moving contact is hollow and is coupled mechanically to a piston, so that when the circuit breaker is tripped the piston causes a flow of oil across the arcing surfaces and through the hollow moving contact. The tests were made at voltages ranging from 3 800 to 13 200 volts, with a corresponding maximum current ranging from 23 000 to 66 000 amperes. In the tests described the separation of the contacts was limited to $1\frac{1}{4}$ in., so that by varying the velocity of the oil and the constants of the circuits it was possible to make the circuit breaker fail or clear as desired. The results of about 400 tests have been plotted to show the relation between the velocity of the oil blast in feet per second and the rate of rise of recovery voltage in volts per microsecond. The successful tests can then be separated from the failures by a straight line passing through the origin. This result is especially interesting as it demonstrates in a particularly convincing manner that the duty of an oil circuit-breaker is directly dependent upon the rate of rise of recovery voltage.

(v) *The Cross-Jet Explosion-pot Circuit-breaker.*—There has recently been developed a shrouded contact which utilizes the gas pressure developed in the explosion-chamber type of shroud to direct a stream of gas and

* *Electrical World*, 1931, vol. 97, p. 400.

oil vapour in a way which makes for maximum turbulence and dispersion. A diagrammatic view of one

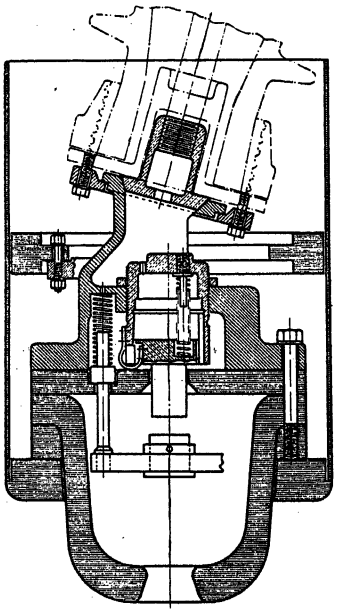


FIG. 3.—Oil-blast explosion pot.

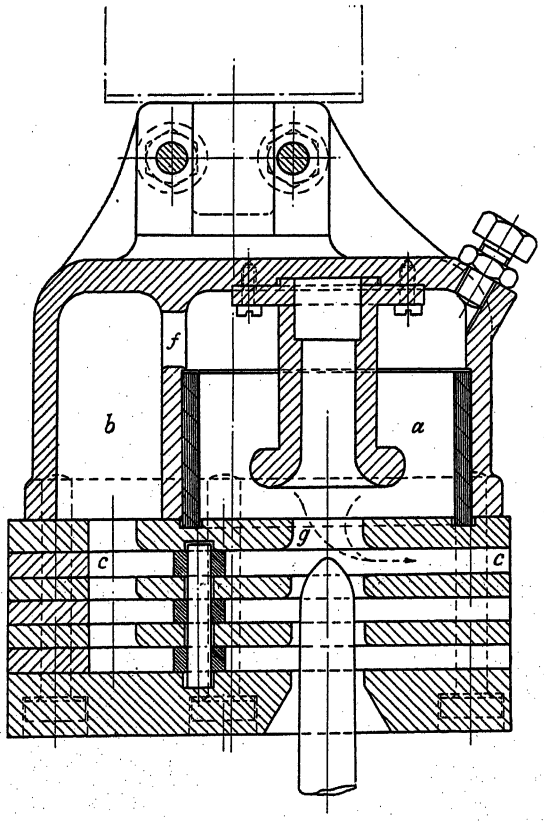


FIG. 4.—Cross-jet explosion pot.

form of this contact is given in Fig. 4. An explosion pot containing the chambers " a " and " b " is fitted with a number of insulation plates forming a series of passages at its open side. The passages have an outline as indicated in the exploded view in Fig. 5. During the first part of the stroke, the pressure generated in chamber " a " is partly relieved by the direct leakage around the contact plunger in the opening " g," and is also communicated to chamber " b " through the opening " f," causing a leakage of oil through the horizontal passages.

When the contact plunger has moved to the position indicated in Fig. 4, most of the oil escaping from chamber " b " will pass along the horizontal passage " cc " towards the arc, thus increasing the rate of generation of gas until the current approaches its zero value. When the value of the current has fallen sufficiently low, the mixing of the comparatively cold oil with the hot gases escaping from chamber " a " through the opening " g " increases the electric strength of the fluid in the direct path of the arc and tends to prevent re-establishment.

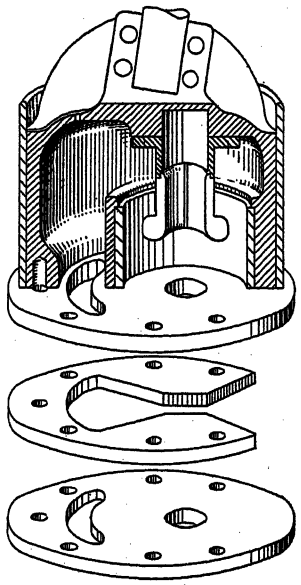


FIG. 5.—Exploded view of cross-jet explosion pot.

Further movement of the contact plunger provides additional horizontal passages and intensifies the action.

(vi) *General Comments on Shrouds.*—There is as yet no general agreement on the precise physical explanation of the operation of devices of this kind. Some engineers consider that the interruption is due to the physical presence of oil in the arc stream at the moment of zero current. Others condemn this as unpractical and consider that the de-ionization is entirely due to the generation of gas at a sufficiently rapid rate in the vicinity of the arc, so that immediately before the moment of zero current sufficient fresh molecules of non-ionized gas are generated to swamp the ionized particles and thus prevent the re-establishment of the arc. According to this theory, it would appear that any movement of oil or non-ionized gas directed towards the arc would be likely to be beneficial.

As another example of the differing views on arc rupture, the theory of Dr. Kesselring* may be mentioned,

* *Elektrotechnische Zeitschrift*, 1930, vol. 51, p. 499.

that what determines whether an arc shall die out or be re-established is the magnitude of the ratio (Rate of fall of temperature)/(Rate of rise of voltage). Without expressing an opinion on the physical accuracy of this statement it may presumably be agreed that anything that promotes a fall of temperature in the vicinity of the arc is likely to be favourable to the final rupture of the current.

It is interesting to note how all these theories have something in common in many of the forms of construction now being tried.

Two of the devices described, the de-ion grid,* and the oil-blast contact,† have progressed beyond the experimental stage and, following extensive series of tests both in the high-power testing laboratory and on public service systems, are already being put into commercial use. These tests have been made on both single-pole and 3-pole units at service voltages ranging from 13·2 kV to 220 kV. The short-circuit kVA interrupted in these series of tests varied up to a maximum of 1 700 000 kVA, so that it may be claimed that these devices have successfully improved the operation of oil circuit-breakers. So far as the authors are aware, the quenched-arc device has not yet been put into commercial service, but it is possible that more experimental work has been done with this device to amplify the results detailed by L. C. Grant‡ where the maximum kVA interrupted was given as 230 000 kVA on an 11 000-volt system.

A large number of tests carried out on the cross-jet explosion pot, and comparative tests with the quick-break contact, show a very marked difference in stress in favour of the shrouded contact. This is due to the fact that with the shrouded contact the quantity of gas generated is limited and the expansion of the gas bubble in relation to the whole quantity of oil in the tank or tank section is restrained.

(4) Certain Design Features.

In this section it is proposed to review some of the design features of an oil circuit-breaker which are most intimately concerned with its behaviour under short-circuit conditions.

(a) Air Volume.

In the past there have been two schools of thought. One regards the air volume merely as a means to avoid high pressures in the tank, on the basis that if gas equivalent in volume, at normal temperature and pressure, to four times the air volume is generated in a tank the absolute pressure is increased fivefold, whereas if only half the air volume had been provided the pressure would have increased ninefold. The other, while still accepting the principle, prefers the use of relatively small volumes with correspondingly higher pressures in order both to secure the assistance of the higher pressure in quenching the arc by increasing the electric strength of the arc path at zero current and to limit the disturbance when the oil above the arc is lifted by the gas pressure and hurled bodily against the top frame of the breaker. When, however, the form of construction includes a shroud for controlling the arc, and thus limits the bodily movement of oil towards the top frame, it would appear reasonable to regard the air volume merely as a cushion for limiting the total rise of pressure.

(b) Head of Oil.

The head of oil required in an oil circuit-breaker may be determined by consideration of purely dielectric requirements or else purely as a function of the breaking capacity. The latter has often been considered the limiting feature. Several writers in the technical Press suggest that the head of oil must be sufficiently large to prevent the formation of a continuous gaseous chimney during arc rupture. No actual data appear to be available to determine the limits of this chimney effect. The conditions must necessarily be different for the various types of contacts. For shrouded contacts the head of oil may be regarded as a function of the dielectric requirement, with due regard to creepage clearance and polluted oil. The plain-break contact is more liable to form a gaseous chimney, and a larger head of oil may be advisable.

(c) Vents.

The function of a vent is to permit the escape of the arc gases without an accompanying discharge of oil. No attempt is made to reduce the initial stress on the circuit breaker; this could only be achieved completely by providing the breaker with an open top.

In principle the most effective form of vent is obtained by providing an expansion chamber between the circuit-breaker hood and the labyrinth or baffled opening into the atmosphere. The opening between the breaker hood and the expansion chamber should be very restricted in area, and is frequently only $\frac{1}{4}$ inch in diameter.

(d) Shape of Tank.

Claims of superiority due to the tank shape are often put forward. These are based on the fact that in a round tank less length of welded seam is necessary and the tank walls may be thinner and are stressed in tension by internal pressure.

The rectangular shape of oil circuit-breaker tanks is usually dictated by the economy in space so highly stressed by operating engineers, particularly for metal-clad gear. The only disadvantage of a properly designed and constructed rectangular tank is its additional weight. In many cases this is more than offset by the saving in space and the convenience in fitting earthed-metal phase barriers—which in turn stiffen the tank.

(e) Contacts.

Contacts have to be considered from two standpoints, (1) their ability to carry continuously their rated load, and (2) their behaviour under short-circuit conditions. The first point does not present any serious difficulty to the designer, except from the standpoint of making them as small in dimensions as may be practicable in order to reduce the dimensions of the tank to a minimum value, or alternatively to provide the largest current rating possible within a given size of tank; also in order to keep the moving contacts as light

* *Transactions of the American I.E.E.*, 1930, vol. 49, p. 431.
† *Ibid.*, 1931, vol. 50, p. 506.
‡ *Journal I.E.E.*, 1930, vol. 68, p. 1089.

as possible to obtain the required speed of break without excessively large accelerating forces. In order to meet short-circuit conditions the contacts in a closed breaker must be able to withstand the prescribed short-circuit current for a period of 1 sec. or more without deterioration. The conductors, contacts, and connections thereto are all subject to comparatively large electromagnetic forces which may permanently deform any part of the circuit which is not designed to withstand such forces without permanent strain. Further, the short-circuit forces may separate the contacts, or some of them, even though the breaker mechanism is latched in the closed position.

When the circuit breaker opens under short-circuit conditions these effects are usually more marked. For example, a breaker having moving contacts of the simple butt and brush type should not be used above a reasonable short-circuit current, otherwise the butt arcing contacts will separate, leaving the current to be broken on the main brush, with resultant burning, rendering it unfit for reclosing. Under slightly different conditions the pressure on the contacts may be so reduced as to produce a sufficiently high contact resistance to cause the contacts to weld together and so prevent the circuit breaker from opening.

These reasons have led to the use of such contacts as the finger and wedge type, which, when mounted in pairs on opposite sides of the contact bar, carry currents in parallel and therefore attract one another and thus increase the contact pressure and correspondingly reduce the contact resistance. On the other hand, when the contact bar has left the fingers, and so long as the current is flowing, the contact fingers are still attracted towards one another, and they must be able to withstand this force without permanent strain. These features are briefly mentioned because, although they are not new, they are not so widely appreciated as they should be, and they explain why ill-constructed circuit breakers, or breakers used above their reasonable short-circuit current rating, are liable to permanent deformation of their contacts, rendering them not only unsuitable for, but even dangerous to reclose after, a short-circuit.

Another form of main contact that has been used by some firms with great success is the Y brush, in which the current is similarly divided between the two portions of the brush to obtain the desired attractive force under short-circuit conditions. This form of construction is inherently robust for withstanding short-circuit stresses, and is economical of space for heavy currents.

The use of explosion pots leads naturally to the use of plunger and socket contacts, which admirably fulfil the desired conditions when carrying short-circuit currents, and can readily be made as robust as desired.

Butt contacts have, by their inherent simplicity, proved attractive to designers, but as a general rule insufficient care and experience have been used to obtain the best results, consequently they have not been as widely used as might have been expected. In the first place the contact pressure has usually been too low, and this definitely sets an upper limit to the permissible short-circuit current. Also the throw-off forces cause difficulty, although the effective latching of the moving contacts in the closed position can be obtained by interposing resilient members behind the stationary contacts, and leaving the moving contact-bar rigid. Fortunately, the simple arrangement of butt contacts, with resilient moving contacts, and without additional main contacts, is quite permissible for moderate short-circuit currents, provided adequate contact pressure is available and the contacts are sufficiently massive.

After butt contacts have been used for rupturing an arc, the surfaces will be found to be rough or mottled, but this condition does not impair their conductivity. The contact resistance, if tested, may even be found to be lower than before the short-circuit. The reason for this is that the heat of the arc burns away the impurities from the surface of the contacts. While the same comments may be made in connection with other forms of contacts, the reservation must be made in the case of sliding contacts that the correct mechanical movement must not be impaired; but only for this reason should oil circuit-breaker contacts require cleaning after a short-circuit.

The next point that arises is as to when contacts should be renewed after a short-circuit. This depends upon whether the mass of the contact has been unduly reduced, whether the contact pressure is still sufficient for the purpose, and whether the desired lead has been maintained between the movement of the contact bar and the separation of the contacts. As the lead is provided to protect the main contacts (where fitted) and also to take advantage of the higher velocity of the contact bar at the end of the desired lead, it is of importance to ensure that these features are not unduly sacrificed. It is impracticable to give quantitative figures of general interest, but the foregoing represents the essential points which, taken into account with the time available for overhaul and the relative importance of the circuit controlled, will enable a reasoned decision to be made.

(*f*) *Contact Pressure.*

Most electrical engineers are willing to subscribe to the theory that, other things being equal, the contact resistance depends upon contact pressure, but few pursue this to its logical and practical conclusion. When the contacts consist of two flat surfaces, whether subdivided or otherwise, it is customary to ascertain whether these surfaces are touching satisfactorily, by trying to insert a thin feeler. If a feeler of, say, 0·0015 in. will not "go," the contact is passed, whereas there may be a gap of 0·001 in. over most of the surfaces, and for such portions of the surface "a miss is as good as a mile." Probably the easiest way of avoiding such an illogical condition is so to shape the contact that only a line contact or even a point contact can be obtained. This procedure has been found very satisfactory by many manufacturers for certain of their apparatus, but for oil circuit-breakers that have to deal with very large short-circuit currents the amount of burning of the contact is reduced by using relatively large surfaces exposed to the arc—always provided that ample pressure is applied so long as the contacts are touching.

(*g*) *Number of Breaks in Series.*

The standard oil circuit-breaker design in this country favours 2 breaks per pole. Mechanically this construc-

tion offers the most simple structure. On the Continent several manufacturers greatly stress the advantage of a multi-break oil circuit-breaker. These are usually of the plain-break type and have from 4 to 10 breaks in series per pole. Multi-break circuit-breakers have also been adopted for a few recent installations in this country.

It has been claimed that for the higher voltages an increase in the number of breaks results in a shorter arcing time, due to the increase in the equivalent speed of break. Test data published in Continental technical literature in support of this claim show improvement compared with plain-break circuit-breakers, but in accordance with the usual Continental practice the tests were carried out on an insulated system. This may possibly explain why other tests carried out on earthed systems show much less improvement, since in this latter case the potential distribution across the breaks is not uniform. It has usually been claimed by advocates of the double-break circuit-breaker that even for high voltages the adoption of a quick break renders it unnecessary to resort to the added complication of the multiple break, owing to the additional contacts and insulation required.

Generally the performance of the multi-break circuit-breaker may be closely compared with that of the quick-break circuit-breaker.

(*h*) *Speed of Break.*

If it could be assumed that a definite break is necessary to interrupt a particular current at a given voltage, then it is clear that the minimum amount of energy would be expended in the arc by attaining this break at the first moment of current zero after arcing has commenced. If the speed is lower than this ideal speed the break is insufficient to permit rupture and the arc persists for at least another half-cycle. If, on the contrary, the speed is higher than the ideal speed, the arc is unduly lengthened, with the result that a needlessly large amount of energy is expended in it.

As the circuit conditions are varied, so it is necessary to vary the speed of break in order to obtain the ideal conditions set forth above. In practice, however, a breaker must be suitable for interrupting widely different currents and sometimes also different voltages. Unless consistency of action is assured, it is impracticable to define exact design limits. In the past it has frequently been stated that no advantage is gained by exceeding certain limiting speeds for comparatively low-voltage circuits. While it is permissible to agree that, in general, high voltages require higher breaking speeds, it is by no means possible in the present state of the art to make a general statement as to the optimum speed for a specific voltage. It is rather a matter for experiment to demonstrate with the required construction and circuit conditions that the arcing time, and consequently the arcing energy, are both reduced to a minimum under the limiting conditions. It is obviously essential to reduce the arcing period to a minimum when the arc energy itself is at a maximum, i.e. when the circuit breaker is breaking the heaviest currents, but it is also necessary to ensure that the arcing time is not unduly long when breaking any other currents within the range of its rating. The different views with regard to speed of break may be largely explained by the varied results it is possible to obtain from a plain-break circuit-breaker when tests are repeated a number of times under the same circuit conditions.

In this respect circuit breakers with shrouded contacts are entirely different, and a much greater measure of consistency can be obtained by careful design. The ideal speed can be regarded as a function of the length of the shroud. This may conveniently be illustrated by comparing two shrouds with the effective length of one only half that of the other. In this case the speed of break in the short shroud should be approximately half that in the shroud which is twice as long. This comparison refers to the actual speed of the moving contacts during the arcing period, and this is controlled by the circuit-breaker mechanism together with the gas pressure generated in the shroud itself. There is a further limitation that with a short shroud a small arc current may be insufficient to produce the required gas pressure for arc extinction. Thus arises the curious phenomenon which is always a source of surprise when first observed, viz. that a breaker which will successfully rupture heavy currents may signally fail with a small current. As an alternative to speed of break it may be a better criterion to ascertain the distance travelled during the first half-cycle of arcing, since a breaker operating efficiently should have travelled far enough in this time to approach a position where the arc cannot restrike.

(*j*) *Arcing Time.*

The effects of the duration of the arc are twofold. Firstly, considering the system into which the circuit-breaker is connected, it is desirable to restrict the duration of the short-circuit to a minimum, and thus remove the fault from the system with the least delay. This does not mean that it would be desirable to break the arc at *any* point of the current wave. If it were possible to break at an instant other than the natural current zero, dangerous oscillations in the system might result. Secondly, considering the circuit breaker, the duration of the arc has considerable bearing on the stresses set up. The natural assumption is that of direct proportion, but this does not actually apply. Nevertheless, the surge and static pressures are greatly influenced by the duration of the arc; thus again it is desirable to restrict the time to a minimum.

In a well-balanced design the ideal circuit breaker should only permit an arcing time of about 1 cycle when rupturing currents approaching its short-circuit rating. For small currents a longer arcing time is permissible, provided the breaker consistently ruptures such currents well before the end of its stroke.

(*k*) *Electromagnetic Forces on the Arc.*

It is well known that the current flowing in a loop produces dynamic forces tending to increase the diameter of this loop. In an oil circuit-breaker a loop is formed by the incoming leads and the moving arm of each pole. The arc becomes part of this loop and, owing to its flexibility, will yield under the influence of the dynamic forces. The consequent shortening of the duration of the arc

can be very marked for heavy rupturing currents on circuit breakers with small pole-centres. It must not be assumed, however, that the decrease in the arcing time with increasing current is entirely due to the electromagnetic forces, as the rate of generation of the arc gases appears to be closely related to the duration of the arc. The effects of the electromagnetic blow-out are very similar to those of increasing the speed of the plain-break circuit-breaker, but it is possible to increase the length of the arc and the stresses set up in the circuit breaker without obtaining the desired reduction of the duration of the arc. The introduction of a " blow-out " device in a circuit breaker must therefore be effected with great care.

(5) Certain System Features.

(a) Recovery Voltage.

" Recovery voltage " may be generally defined as that voltage which occurs across the contacts of a circuit breaker after the interruption of a short-circuit current by the breaker.

Consider a symmetrical 3-phase fault. The power factor of the load is the phase relation between the line voltage and current. The fundamental voltage across the contacts of the breaker is approximately in phase with the line current. As the breaker opens, the voltage across the contacts increases, and the line voltage on the load side of the breaker decreases. When rupture is complete the voltage across the contacts represents the phase voltage of the system at that point, and is determined by the e.m.f. of the generators and any normal load left on the system. Hence the magnitude and phase of the recovery voltage are affected by the rapidity of the response of the alternator e.m.f. to changes in load, by the remaining load on the system, and by the difference in phase angle between the fault current and the remaining load.

On the application of a short-circuit the e.m.f. of the alternator falls in a similar manner to the current-decrement curve. The shape of the voltage-decrement curve depends upon the constructional features of the machines. In general anything that promotes a steep decrement curve is likely to encourage a corresponding rise of voltage when the short-circuit is removed. Consequently a decrease in the reactance of the machine will tend towards a high value of recovery voltage; and just as the sub-transient reactance is a determining factor for the initial rush of current, so it also controls the recovery voltage during the all-important moment immediately after the rupture of a short-circuit current.

(b) Rate of Rise of Recovery Voltage.

Whenever a voltage is suddenly applied to an electrical system, transient oscillations are set up. The natural frequency of these oscillations depends upon the proportions of reactance and capacitance, and is frequently so high that it is not recorded by the ordinary electromagnetic oscillograph, though it can readily be shown by the cathode-ray oscillograph. Under normal conditions these oscillations do not present any difficulty, but when the voltage is applied by the sudden removal of a short-circuit current the addition of a high-frequency voltage to the power-frequency voltage proves particularly inconvenient at the contacts of the circuit breaker clearing the fault.

In practice the actual curve of recovery voltage may be the resultant of a number of transients of different frequencies. The higher frequencies are, however, the more troublesome, so that any decrease in the capacitance adjacent to the circuit breaker makes its duty more difficult. On the other hand, any resistance connected across phases has a damping effect. This explains why short-circuit tests on circuit breakers are more severe when carried out adjacent to testing plant which does not supply any other load; the rate of rise of recovery voltage is higher. The effect on the duration of the arc is illustrated in Fig. 6, which is based on data abstracted from a paper by Spurck and Strang.*

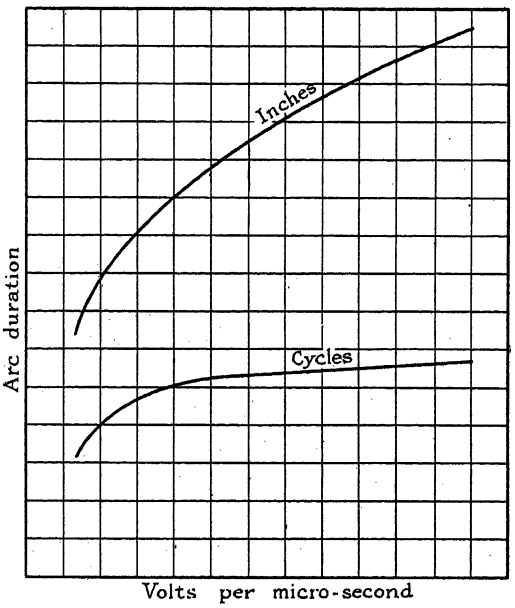


Fig. 6.—Effect of rate of rise of recovery voltage on arc duration.

A detailed study of the magnitude and rate of rise of recovery voltage has been made by Park and Skeats.†

(c) Sequence Impedance.

The effect of sequence impedance on fault currents and voltages has been carefully analysed by Evans and Wright.‡ By the use of equivalent networks for positive, negative, and zero sequence impedance they have evaluated fault currents and voltages for different ratios of these impedances. The resultant curves illustrate clearly the additional duty thrown on to a circuit breaker by a high zero-sequence impedance, thus confirming that the most onerous phase faults are these in which there is no earth connection between the fault and the neutral point of the generator or transformer supplying the system.

Another effect that is clearly illustrated by this

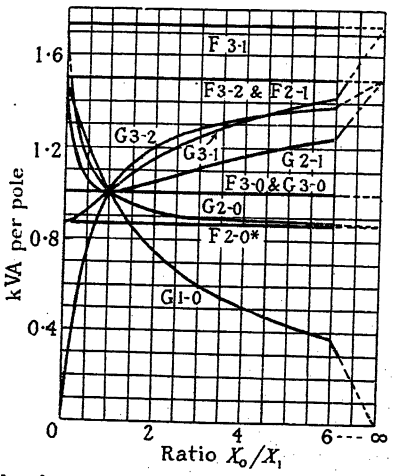
* *Transactions of the American I.E.E.*, 1931, vol. 50, p. 513.
† *Journal of the American I.E.E.*, 1930, vol. 49, p. 1017.
‡ Paper read at the American I.E.E. Middle Eastern District Meeting, March 1931.

treatment is shown in Fig. 7, taken from the same paper. This shows the effect on the kVA rupturing duty of each pole of a circuit breaker when the current is broken simultaneously or successively on the various poles, according to the value of the ratio X_0/X_1, where X_0 is the zero-sequence reactance and X_1 is the positive-sequence reactance for the particular case when the negative-sequence reactance is equal to the positive-sequence reactance and all resistances are negligible.

(6) Short-Circuit Testing.

(a) General.

In the early days of oil circuit-breakers the need of suitable equipment for testing under short-circuit conditions was realized. Unfortunately for the art, however, such equipment is large and costly, and so long as switchgear was regarded as equipment of minor importance



* Faulted conductors assumed at earth potential after breaker opening.

Fig. 7.—Effect of sequence reactance on rupturing duty.

Each curve shows the kVA of a pole whose opening is a particular step in the clearing of a fault, and its labelling indicates the number of poles closed both before and after this opening, and whether the fault is earthed (G) or insulated from earth (F). The ordinate is the ratio of the product of the symmetrical R.M.S. current through a pole before opening, to the product of the 3-phase short-circuit current and the normal line-to-neutral voltage. All resistances are assumed to be equal to zero.

there remained little chance of improvement. Gradually switchgear assumed greater and greater importance, until to-day it is one of the most vital portions of the plant of an electricity undertaking.

Even yet, however, switchgear does not secure its due measure of regard. While individual manufacturers and the Electrical Research Association have carried out considerable work, their efforts are naturally circumscribed by the size of the equipment available for their use. In the United States similar conditions apply, except that in their case the electricity undertakings realize the importance of this issue to themselves and have frequently carried out short-circuit tests on their systems, thus obtaining valuable information with larger power available, and under actual operating conditions, which it was impossible to obtain in a high-power laboratory.

Similarly in Australia and elsewhere, short-circuit tests have been carried out by electricity undertakings, thus maintaining the natural outlook of a responsible engineer who desires to prove for himself the effectiveness of any apparatus he may be using.

Why, then, has this course not been followed more extensively in Great Britain? It is not for lack of personnel or equipment. It can hardly be because of the cost involved, as this is a comparatively small factor compared with the benefits to be obtained by proving the equipment installed and ensuring a satisfactory choice for future equipments.

Short-circuit tests may be carried out either as a research investigation or else to prove a given design in line with engineering requirements. The costliness of a testing plant can readily be appreciated by considering the component parts which make up a modern high-power laboratory. A high-capacity generating plant of low reactance is the first essential. The nominal rating of short-circuit testing generators may be as high as 100 000 kVA for one single unit, giving first half-cycle capacities of up to 1 500 000 kVA. To cover a voltage range from 11 kV to 220 kV, transformers of exceptional design are necessary. For successful research investigation it is essential to have available a large range of current values at any desired voltage. Current-limiting reactors with multiple tapping arrangements are generally found to be most suitable for this purpose. The current-carrying parts in the whole testing equipment require special consideration in regard to the electromagnetic forces. The recording and measuring instruments must be very sensitive and capable of producing permanent records.

Even with a testing plant of this character the effective range is very limited, so that unless still larger testing plant is available supplementary tests on large power networks are essential for proving the performance of the breakers that have the most important duty to carry out, namely those installed on large and important systems.

Fortunately the oil circuit-breaker designer is not left entirely without means for obtaining data, and the following procedure has been found satisfactory for checking designs of circuit breakers in which the arc is controlled by means of a shroud. Firstly, a series of tests is made, ranging up to full voltage or over, with rupturing currents of about 500 to 1 500 amperes, to determine that the breaker can handle the required voltage when the minimum assistance is obtained from the shroud. As previously explained, the arcing time may be longer for small currents, but, provided the arc is consistently broken within the sphere of influence of the shroud and other conditions are satisfactory, the voltage rating is justified. Next, a series of tests is made, ranging up to full current or over at the highest voltage that can conveniently be obtained. These tests confirm that the mechanism, contacts, and shrouds, are capable (or incapable) of handling such currents without failure or undue deterioration.

A successful series of repeated tests in both categories, including B-2-M-B duty-cycle tests as laid down in B.S.S. No. 116, can be regarded as proving a shrouded circuit-breaker under the two extreme limiting conditions of voltage and current. Confirmatory tests on full power have indicated that this attitude has been justified.

(*b*) *Short-Circuit Test Arrangements.*

It is the general practice of the company with which the authors are associated to short-circuit the alternators they build, in order to prove conclusively before dispatch that they are in every way capable of withstanding a condition that may at any time be experienced in service. When this test is carried out it provides a natural opportunity for research tests on oil circuit-breakers. The necessary test-records are obtained by means of the oscillographic equipment, which is housed adjacent to the generator testing department.

(i) *Short-Circuiting Switch.*—When the breaker is closed ready for tripping automatically under fault conditions, the short-circuit is applied by closing the short-circuiting switch. For generator voltages this consists essentially of a series of contacts carried on insulated cross-bars retained in position by a latch which can be released electrically, allowing the contacts to fall into the closed position under the action of gravity and strong compression springs. Insulation barriers are provided to avoid the possibility of a short-circuit across phases.

(ii) *The Oscillograph.*—The electromagnetic oscillograph was designed and constructed in 1924 in the workshop of the company's research department. It is capable of recording 9 quantities simultaneously on a film 8 inches wide. Six of the elements are of the usual type, fitted with permanent magnets and capable of recording currents or other quantities, variations in which can cause proportional variations in current. The other three elements are arranged to record the instantaneous product of two currents, and can therefore be connected to record instantaneous power.

By means of nine small prisms, a beam of light from an arc lamp is split up and directed on to the mirrors of the nine elements. The beams of light reflected from the elements then pass through finely adjustable slits and thence through a cylindrical lens, which focuses them on to the photographic film in the camera. The camera is of the drum type and is capable of taking films of any size up to 8 inches in width and 36 inches in length. In addition to a hand shutter, a rapid electrically-operated shutter is provided, which is controlled by drum contacts on the camera shaft and operates in conjunction with the timing circuits. By this means it can be ensured that a film is not exposed more than once, and that the phenomenon under investigation, e.g. the operation of a circuit breaker, does not start until the beginning of the film has passed the shutter aperture. Also, the apparatus can be set so that the whole or any one of three portions of a 36-inch film can be exposed at will. As a film length of 12 in. is ample for all ordinary tests, this device enables duty-cycle tests to be performed in rapid succession without reloading the camera. The camera drum is driven by an adjustable-speed motor through belts and pulleys, and a large range of speeds may be obtained by using different pulley combinations.

A photographic dark-room has been equipped, so that the results of a test may be roughly assessed from the film a few minutes after it has been exposed, thus enabling the conditions for the next test to be decided.

(iii) *The Travel Indicator.*—This device consists of a rheostat, the arm of which is rigidly coupled to the part of the circuit breaker the travel of which it is desired to record. As shown diagrammatically in Fig. 8, the rheostat R is connected in series with an oscillograph element O, a battery B, and a series resistor. As the circuit breaker operates, the rheostat causes the current

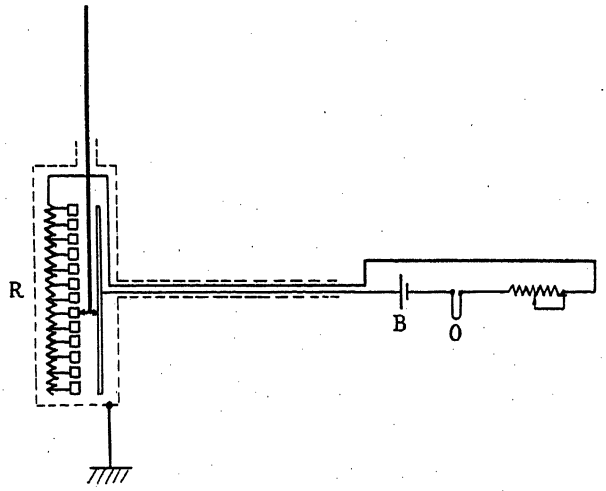


Fig. 8.—Diagram of travel indicator.

in the circuit, and hence the element deflection, to vary in a series of clearly-defined steps.

The use of a travel indicator is essential to determine when the arc tips separate, and is also useful in determining the speed of movement and whether the motion of the contact bar is regular and consistently progressive.

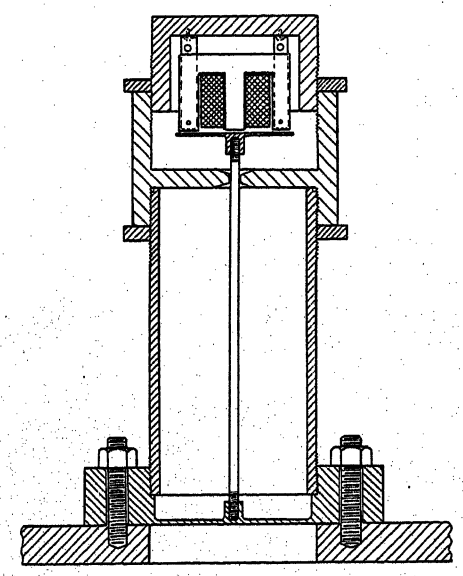


Fig. 9.—Pressure-measuring device.

(iv) *The Pressure-Measuring Device.*—The pressure acts on a diaphragm placed where it is desired to measure the pressure. As shown in Fig. 9, the diaphragm is coupled by means of a non-magnetic steel rod to an armature which forms part of the magnetic circuit of a laminated electromagnet. The deflection of the

diaphragm causes a variation in the reluctance of the magnetic circuit, and the winding of the electromagnet forms one arm of a bridge network. The resultant variation in the balance of the network is recorded by an oscillograph element.

The leads from the coil to the bridge network are carefully twisted to avoid inductive interference and are enclosed in an earthed metal tube for a considerable distance from the breaker as a protection against possible

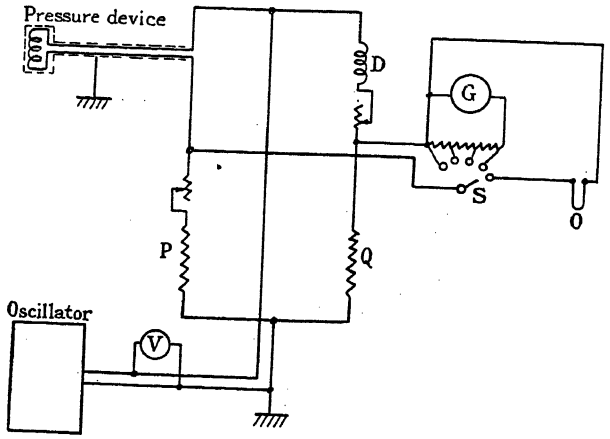


FIG. 10.—Diagram of pressure-measuring device.

damage from arcs. The network is shown in Fig. 10. In series with the pressure device is a non-inductive resistance P, capable of a small adjustment. The other two arms consist of a fixed non-inductive resistance Q and a dummy electromagnet D, similar to that in the pressure device except that the armature is fixed and can be adjusted so as to vary the air-gap over a moderate range. A small variable resistance is provided in series with D. The network is supplied by a valve oscillator giving a few volts at 1 000 cycles per sec., and is earthed at one point. The oscillograph element O is connected across the diagonal of the bridge when the switch S is thrown over to the extreme right-hand position. If now P is equal to Q and the impedance of D is adjusted until it is equal in magnitude and phase to that of the pressure device when the pressure is zero, no current will flow through the oscillograph element. If pressure acts on the diaphragm of the pressure device, the balance of the bridge is disturbed and a 1 000-cycle current will flow through the oscillograph, the amplitude of the deflection being proportional to the pressure. The pressure record therefore takes the form of a 1 000-cycle band, the width of which is proportional to the pressure.

(v) *Procedure in Carrying-out Tests.*—The connections for a typical test on an oil circuit-breaker are shown in Fig. 11. Between the circuit breaker under test and the alternator supplying the testing current is connected a master switch. The control connections are so arranged that the operation of either the master switch or the test breaker can be effected by the oscillograph timing-circuits.

The oscillograph elements available may be employed in various ways, a typical allocation being shown below.

Element number	Type	Quantity observed
1	Permanent magnet	Line voltage
2	Permanent magnet	Line current (Phase A)
3	Permanent magnet	Line current (Phase B)
4	Permanent magnet	Line current (Phase C)
5	Permanent magnet	Travel
6	Permanent magnet	Oil pressure
7	Power	Arc energy (Phase A)
8	Power	Arc energy (Phase B)
9	Power	Arc energy (Phase C)

The sequence of events during the progress of a test can be obtained by a study of Fig. 11. When all is

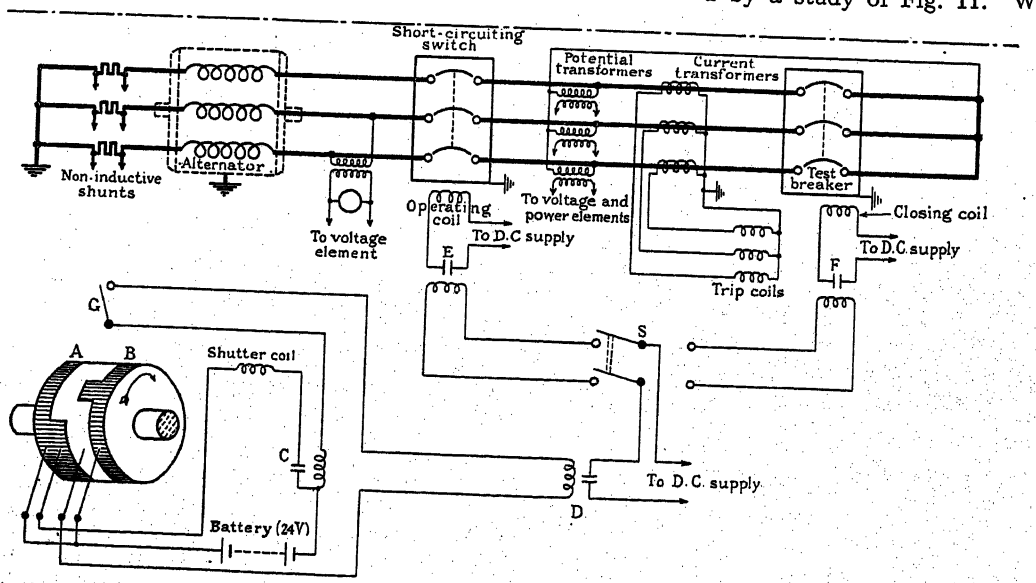


FIG. 11.—Diagram for short-circuit tests.

ready the control switch G is closed and the alternator driving-motor tripped out simultaneously. From this point the whole of the operations are automatic. The adjustable time-lag relay D of the pendulum type operates as soon as the short contact B on the camera commutator (driven at half camera speed) arrives opposite its brush. This relay closes the supply to one of the two adjustable time-relays E and F, through the 2-way switch S, the position of which is previously set according to whether the test is a " break " test or a " make-break " test. The relay E operates the closing coil of the master breaker, whilst F operates the closing coil of the breaker under test. As the camera revolves, the long contact A eventually reaches its brush, at which moment the camera shutter coil is energized and the spring-loaded shutter opens.

The quick-acting lock-in relay C, which is closed at the moment relay D is energized, prevents the shutter opening before the initiation of the test. The film is so located on the camera drum that its start coincides with the position of contact A, and hence the shutter opens at the start of the film. The actual short-circuit occurs 3 or 4 cycles after the closing of contact A, this being dependent on so setting the pendulum relay D that the time delay on the camera commutator between the leading trips of contacts B and A is slightly less than the delay occurring between the operation of relay D and the closing of the switch.

(vi) *Prevention of Fire and Results of Accidents.*— Whenever short-circuit tests are carried out it is usual for the observers to stand sufficiently remote from the switch under test in order to avoid any risk of damage from fire or explosion. Firemen with suitable chemical appliances are also near at hand. There have been occasions when these precautions have been fully justified, although normally there is little indication that a breaker has operated. A slight movement of the circuit-breaker mechanism; a wisp of smoke from the vent; a shudder from the whole circuit breaker when dealing with large powers, particularly when the current is heavy; some movement of the main conductors, unless they are suitably secured to withstand the short-circuit current; these are some of the features that may be observed visually. In the older types of breakers oil-throwing was quite prevalent, but means for overcoming this are being increasingly employed.

When a breaker is tested to destruction, there is always a danger of the gas vapours igniting, and in such cases the flames rise rapidly 20 or 30 ft. into the air. The heat is very intense while it lasts, but can be rapidly controlled.

Occasionally external arcing takes place between conductors which apparently are separated by an ample clearance. This is much more noisy, and therefore alarming to the uninitiated, but with proper protective devices the arc is rapidly quenched and little damage is done unless an excess voltage has been applied to the equipment and caused internal damage.

(c) *Calculation of 3-Phase kVA.*

It is to be regretted that as yet there is no universally-agreed method of calculating from test oscillograms the power broken. In any one country, and better still internationally, it is essential to standardize such matters as this. In choosing a suitable method, the first consideration must be towards the accurate evaluation of the essential quantities involved. If this leaves any choice due to the complex nature of the quantity required and the uncertainty of the precise physical relations involved, then preference should be given to the simpler form, which can most readily be shown graphically and enumerated arithmetically.

It is usual for British manufacturers and users to assess the breaking capacity of circuit breakers in kilovolt-amperes. The method of calculation to be adopted is laid down in B.S.S. No. 116—1929. The current to be used is the R.M.S. current at the moment of contact separation, and this is obtained from the current film by selecting the appropriate moment from the travel indicator. The voltage prescribed is the recovery voltage after the current has been interrupted.

In America the use of kilovolt-amperes has at times been discouraged, since it was considered more specific to refer to the arc-amperes and to associate this with line voltage. More recent work on the effect of recovery voltage and the rate of rise of this voltage will probably effect some modification in their practice, and additional data are being collected prior to a reconsideration of the problem.

On the Continent an attempt has been made to avoid the irrational method of calculating the kVA from the product of currents and voltages which are not produced simultaneously. This is achieved by producing the envelope containing the regular portion of the recovery voltage until it meets the vertical line representing the moment of contact separation. The voltage thus obtained is called the "active voltage" and is used with the phase current at the same moment for estimating the effective kVA.

It will be noted that the majority of countries appear to be in agreement that the breaking capacity of a circuit breaker shall be expressed in kilovolt-amperes, and that the current factor is generally accepted as defined in B.S.S. No. 116. The voltage factor is a much-disputed quantity. The use of the recovery voltage, though not universally accepted, is more general and was recommended by the International Electrotechnical Commission in 1930. This appears to be a logical step when it is considered that the magnitude and the rate of the voltage building-up across the circuit-breaker terminals after every current zero are responsible for the restarting of the arc.

The rate of rise of the recovery voltage is still a quantity to be investigated more closely and is not at present seriously considered in the classification of circuit-breaker performance.

(7) Short-Circuit Tests.

References to published reports of short-circuit tests on various forms of shrouded contacts have already been given. In this section an account is given of three recent series of tests on the cross-jet explosion pot.

Investigation No. 112.

This investigation was carried out on the 23rd–26th January, 1931, on a Type K5 33 000-volt, 600-ampere,

TABLE 1.

Short-Circuit Tests on Type K5 Oil Circuit-Breaker (Investigation No. 112).

Test number	Line voltage	Recovery voltage	Breaking current	3-Phase kVA		Duration, half-cycles		Length of arc, inches per break	Pressure above oil	Remarks
				On line volts	On recovery volts	Of short-circuit	Of arc			
	kV	kV	amps. (R.M.S.)	kVA	kVA			in.	lb./sq. in.	
114	12·5	10·8	3 200 3 600	73 500	63 500	4·8 4·8	2·0 1·6	1·2	none	No visible distress
115	26·2	22	7 900 7 600 8 800	368 000	310 000	7·5 7·0 7·6	2·2 1·6 2·2	1·4	7	No visible distress
116	12·5	Oscillograph record missed							23	No visible distress
117	25·4	20·4	8 100 7 500 8 350	354 000	284 000	7·0 7·0 7·4	1·5 1·1 1·5	1·0	none	No visible distress
118	30·8	24·8	9 800 9 600 10 600	535 000	430 000	6·9 7·4 7·6	1·3 1·7 1·7	1·0	none	Breaker suitable for further service without attention

TABLE 2.

Short-Circuit Tests on Type K5 Oil Circuit-Breaker (Investigation No. 117, standard two breaks per pole).

Item number	Line voltage	Recovery voltage	Breaking current	3-Phase kVA		Duration, half-cycles		Length of arc, inches per break	Remarks
				On line volts	On recovery volts	Of short-circuit	Of arc		
	kV	kV	amps. (R.M.S.)	kVA	kVA			in.	
1	25·0	21·5	3 870 2 260 3 060	133 000	114 000	6·2 5·9 6·2	3·4 3·1 3·4	2·64	No visible distress
2	26·6	22·1	2 560 3 420 2 560	131 000	109 000	5·6 7·0 7·0	3·1 4·4 4·4	3·3	No visible distress
3	26·6	22·4	3 660 2 340 3 970	153 000	129 000	6·0 6·5 6·5	3·7 4·2 4·2	3·3	No visible distress
4	28·2	23·7	3 090 3 450 4 800	185 000	155 000	6·0 6·0 5·7	3·6 3·6 3·3	2·64	No visible distress
5	28·2	23·1	4 700 3 570 2 840	181 000	149 000	5·7 6·0 6·0	3·3 3·6 3·6	2·64	No visible distress
6	31·4	26·8	5 260 3 120 3 900	222 000	190 000	6·2 5·9 6·2	3·7 3·4 3·7	2·8	No visible distress
7	31·4	26·8	4 020 3 180 5 180	224 000	192 000	5·9 5·9 5·6	3·4 3·4 3·1	2·47	No visible distress
8	33·0	27·2	5 700 3 310 4 350	254 000	210 000	6·2 6·8 6·8	3·4 4·0 4·0	3·14	No visible distress
9	33·0	27·2	4 000 4 880 3 480	236 000	194 000	7·8 7·5 7·8	4·1 3·8 4·1	3·3	No visible distress
10	33·0	26·9	3 410 2 680 3 730	187 000	153 000	15·0 15·0 14·3	6·0 6·0 5·3	2·8	Breaker speed reduced by removing two throw-off springs. No visible distress
11	33·0	27·2	2 950 2 680 3 370	171 000	141 000	15·8 15·8 15·4	6·4 6·4 6·0	2·8	Breaker in good condition. Contacts slightly burned—other parts as new

To face page 716.]

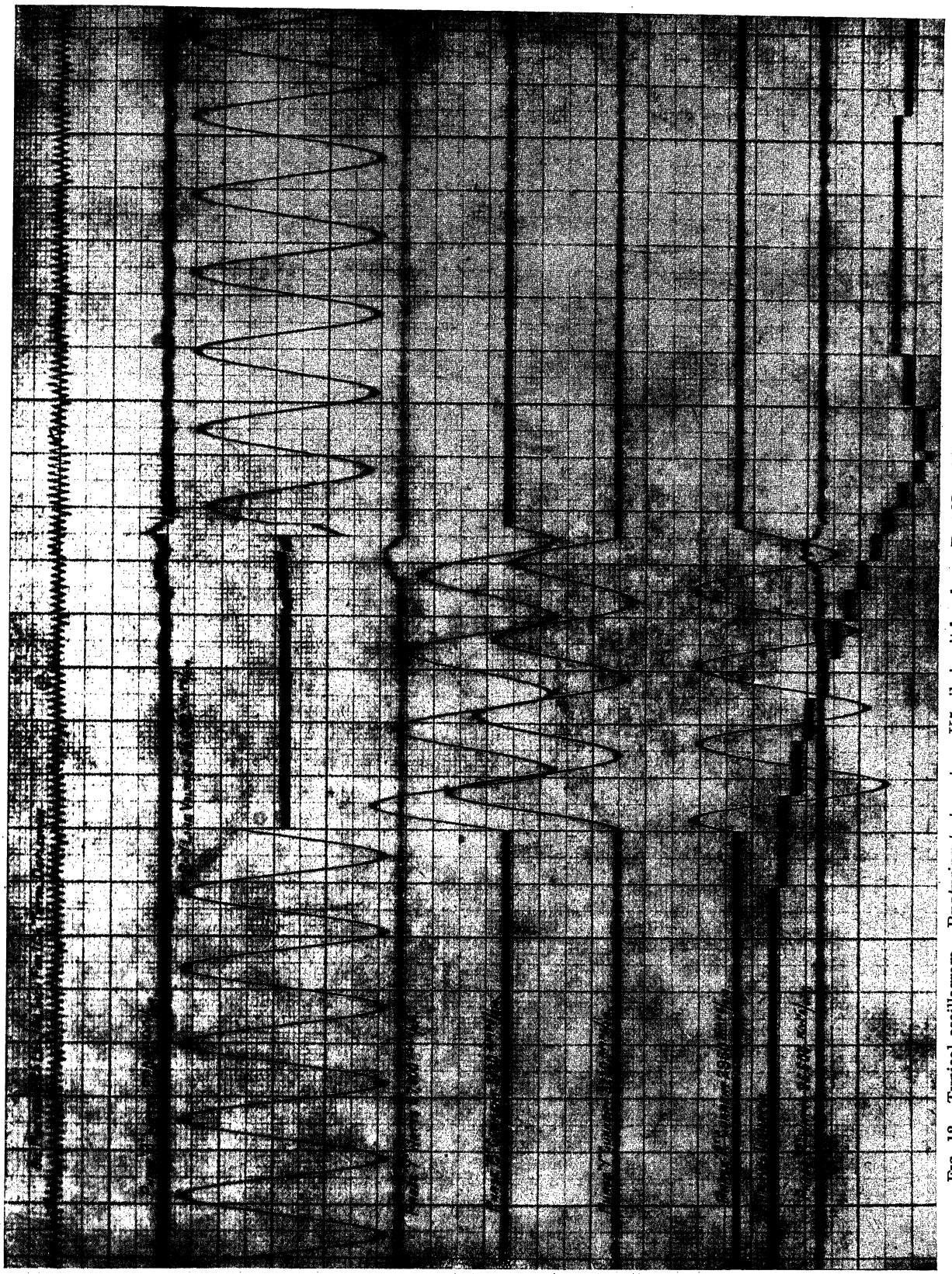


FIG. 12.—Typical oscillogram. Rupturing test on type K5 oil circuit-breaker. Test No. 12A. Test voltage 33 000 volts. Duty cycle B.

metal-clad, oil circuit-breaker fitted with cross-jet explosion pots.

The testing plant consisted of a 3-phase 50-cycle 100 000-kVA motor-driven alternator running at 1 500 r.p.m. in conjunction with a 100 000-kVA 3-phase transformer with sectionalized secondary winding. The alternator was connected to the transformer, with the 33-kV star point earthed, a master breaker, and thence to the K5 breaker under test. For all tests an unearthed 3-phase fault was applied to the test breaker. The K5 breaker, as modified to accommodate the cross-jet contact shrouds, had a cross-bar travel of 7·25 in. and a break of 2 × 5·25 in. All 3 phases were accommodated in one tank having steel divisions between the phases, the volume of the tank being 100 gallons.

Table 1 shows the test data obtained. It is seen that the breaker successfully cleared 430 000 kVA

TABLE 3.

Short-Circuit Tests on Type K5 Oil Circuit-Breaker (Investigation No. 117, one break per pole).

Item number	Line voltage	Recovery voltage	Breaking current	3-Phase kVA		Duration, half-cycles		Length of arc, inches per break	Remarks
				On line volts	On recovery volts	Of short-circuit	Of arc		
	kV	kV	amps. (R.M.S.)	kVA	kVA			in.	
12	18·0	15·4	2 370 1 480 2 450	65 300	56 000	7·1 7·5 7·5	3·6 4·0 4·0	2·95	No visible distress
13	20·0	16·3	2 970 2 660 1 700	84 500	69 000	8·0 7·6 8·0	4·1 3·7 4·1	2·95	No visible distress
14	23·5	18·3	3 620 2 220 2 650	115 000	89 500	7·5 7·8 7·8	3·9 4·2 4·2	3·05	No visible distress
15	26·6	21·4	4 200 3 150 2 420	150 000	120 000	7·5 7·8 7·8	3·8 4·1 4·1	3·05	No visible distress
16	28·2	23·8	2 680 2 990 3 480	147 000	124 000	8·1 7·85 8·1	4·15 3·9 4·15	3·05	No visible distress
17	29·8	25·2	4 160 3 100 2 550	169 000	148 000	8·25 7·9 8·5	4·45 4·1 4·45	3·3	No visible distress
18	31·4	26·6	2 500 4 000 3 530	187 000	158 000	7·9 8·2 8·2	4·0 4·3 4·3	3·3	No visible distress
19	33·0	27·4	2 860 4130 4 000	209 000	174 000	7·9 7·65 7·9	4·25 4·0 4·25	3·3	No visible distress
20	34·5	28·9	5 160 3 310 3 850	246 000	206 000	7·5 8·0 8·0	4·0 4·5 4·5	3·3	No visible distress
21	29·8	25·2	4 080 3 050 2 720	168 000	143 000	9·3 9·3 8·6	5·0 — 4·3	3·95	Centre phase with both breaks shorted—outer phases one break on each shorted. No distress
22	31·4	26·0	4 220 3 830 3 220	205 000	169 000	9·3 9·3 8·6	5·0 — 4·3	3·95	Centre phase with both breaks shorted—outer phases one break on each shorted. No distress
*23	33·0	26·4	3 080 2 720 2 910	166 000	133 000	14·3 13·8 14·3	9·2 8·8 9·2	3·3	Breaker speed reduced by removing two throw-off springs. No visible distress
*24	34·5	28·4	3 300 4 190 3 400	217 000	172 000	13·8 11·2 13·8	10·8 9·5 10·8	3·8	Breaker in good condition. Contacts and shrouds slightly burned

* M-B shots.

(calculated on recovery volts) without any signs of distress. The condition after these tests was, in fact, such that the breaker could have been put into service without any attention whatever. It may be noted that the arc was extinguished in all cases within 27 per cent of the break length, and that the arcing time never exceeded $2\frac{1}{2}$ half-cycles.

Investigation No. 117.

In order to check the behaviour of the K5 breaker fitted with cross-jet contact shrouds at medium powers, a further investigation was carried out on the 9th May, 1931. For this investigation the testing plant consisted of a 48 000-kVA 6 600-volt 1 500-r.p.m. 3-phase 50-cycle alternator, with its windings specially connected to give 11 000 volts between phases, in conjunction with a 45 000-kVA 11 200/34 500-volt transformer, the star point being earthed on the high-voltage side.

The supply from the alternator was taken through a 3-phase 11 000-volt air-insulated isolating switch to the power transformer, and from the secondary of the power transformer to the test breaker via a Type K4A metal-clad oil circuit-breaker, which was used as the master closing breaker. The test breaker was tripped by means of an auxiliary supply, and special timing arrangements were made so that the instant of parting of the test-breaker arcing-contacts occurred about 1 cycle after the initiation of the short-circuit by means of the master closing breaker. This arrangement was adopted in order to obtain the maximum possible short-circuit kVA from the available apparatus.

The results were recorded by means of the 9-element oscillograph previously described, and for all tests a 3-phase unearthed fault was applied. A typical oscillogram is shown in Fig. 12 (see Plate facing page 716). This shows a novel feature suggested by Mr. F. Hough, whereby the curves appear on squared paper in order to facilitate the interpretation of the results.

Three groups of tests were carried out. For tests Nos. 1 to 11 (Table 2) inclusive the breaker was arranged as it would normally be in service, i.e. 3 poles with 2 breaks per pole. For tests Nos. 12 to 20 (Table 3) inclusive, the breaks on the short-circuited side of the breaker were bridged by means of special contacts, giving a 3-pole breaker with 1 break per pole. For tests Nos. 21 to 24 inclusive the single break on the line side of the middle pole was also bridged, giving a 2-pole breaker with 1 break per pole. (It should be noted that although the middle pole, physically, was bridged, it was the red phase, electrically, which had no breaks. This was due to an unavoidable transposition of phases in connecting up.) As a further variant of the conditions for tests 10, 11, 23, and 24, two throw-off springs were removed so as to reduce the speed of travel.

Tables 2 and 3 show the results of tests obtained during this investigation. In none of the tests was there any sign of distress when the breaker cleared, and apart from the movement of the mechanism and the usual thud accompanying the clearing of the short-circuit the only other indication of the short-circuit having been cleared was occasional wisps of smoke from the vents. A notable feature of the behaviour of this breaker was the clean and decisive interruption of the arc. The oscillograph records show that in all tests the arc energy and the tank pressures were too small to be measured. The arcing times are all consistently short, never being more than 5 half-cycles except for tests 10, 11, 23, and 24, when the speed of travel was deliberately reduced to about half that obtained in the remainder of the tests. It is interesting to note, however, that in spite of the increased arcing times in tests 10, 11, 23, and 24, the length of break for arc extinction is consistent with the figures obtained for the higher-speed break.

The K4A breaker, used as the master closing breaker, was also fitted with cross-jet contact shrouds, and during the progress of this investigation and of another series of tests not recorded here this master breaker actually closed on 40 short-circuits. Examination of the breaker at the completion of the full series of tests showed remarkably little burning of the contacts and no distress.

TABLE 4.

Short-Circuit Tests on Cross-Jet Explosion Pots Fitted to a Type FHKO–139–54B Oil Circuit-Breaker (Investigation No. 409).

Test number	Line voltage	Breaking current	Single-phase	Duration, half-cycles		Length of arc, inches per break	Pressure below oil	Average kV per inch of arc	Remarks
				Of short-circuit	Of arc				
	kV	amps. (R.M.S.)	kVA			in.	lb./sq. in.	kV	
31	66	700 (est.)	46 000	Current record missed		7	12	4·7	Cleared—no disturbance
32	66	760	50 000	10	3·6	5·5	4	6·0	Cleared—no disturbance
33	66	770	51 000	10	3·5	5·3	12	6·2	Cleared—no disturbance
34	72	830	60 000	10	5·0	8·3	4	4·3	Cleared—no disturbance
35	72	830	60 000	10	5·0	6·8	low	5·3	Cleared—no disturbance
36	72	880	63 360	17	13·3	24·5	4	1·47	Cleared—slight jar
37	72	1 400	100 800	16	10·7	23	10	1·56	Cleared by station breaker shortly before test breaker reached end of stroke

Investigation No. 409.

This investigation was carried out on the 13th–16th July, 1931, on a single-phase 110-kV 600-ampere Type FHKO—that is 139–54B—oil circuit-breaker specially fitted with cross-jet explosion pots designed for use in a 66 000-volt K10 circuit breaker.

The testing plant comprised a 100 000-kVA motor-driven alternator with multiple windings in conjunction with a 280 000-kVA transformer. All tests were single-phase from 3 800 volts to 96 000 volts at 25 cycles. For the lower voltages one pole of the transformer was earthed; above 48 kV the mid-point of the transformer winding was earthed. The FHKO breaker had a normal stroke of 28 in., the length of a single break being 24½ in.; this compares with 14 in. for the K10 breaker for which the cross-jet explosion pots were designed.

Table 4 shows the results of the first series of tests on this breaker. It will be noted that on test No. 37 the short-circuit was cleared by the station breaker before the test breaker had reached the end of its travel. Examination of the contacts after this test showed that

TABLE 5.

Short-Circuit Tests on Cross-Jet Explosion Pots Fitted to a Type FHKO–139–54B Oil Circuit-Breaker (Investigation No. 409).

Test number	Line voltage	Breaking current	Single-phase	Duration, half-cycles		Length of arc, inches per break	Pressure below oil	Pressure in explosion pot	Average kV per inch of arc	Remarks
				Of short-circuit	Of arc					
	kV	amps. (R.M.S.)	kVA			in.	lb./sq. in.	lb./sq. in.	kV	
38	56	640	35 840	11	3·5	5·3	6	—	5·3	Cleared—no disturbance
39	72	870	62 640	11	4·3	7·3	6	—	4·9	Cleared—no disturbance
40	72	880	63 360	9	4·0	6·5	10	—	5·5	Cleared—no disturbance
41	72	870	62 640	10	4·4	7·0	10	—	5·1	Cleared—slight gas
42	72	1 500	108 000	9	3·8	6·5	6	—	5·5	Cleared—slight gas
43	72	1 500	108 000	10	4·4	7·8	6	—	4·6	Cleared—slight gas
44	72	1 500	108 000	10	4·0	6·8	6	—	5·3	Cleared—slight gas
45	96	580	55 680	12	5·4	9·3	10	—	5·1	Cleared—no disturbance
46	96	600	57 600	10	4·0	6·5	6	—	7·4	Cleared—no disturbance
47	96	620	59 520	13	6·8	13·3	6	—	3·6	Cleared—no disturbance
48	96	600	57 600	10	4·6	7·8	—	—	6·1	Cleared—no disturbance
49	96	970	93 120	9	3·0	5·0	low	—	9·6	Cleared—no disturbance
50	96	970	93 120	9	3·5	5·8	6	—	8·1	Cleared—no disturbance
51	96	960	92 160	11	4·0	6·8	6	—	7·0	Cleared—no disturbance
52	13·2	7 000 (est.)	92 400	Current record		missed		124	—	Cleared—no disturbance
53	13·2	7 000	92 400	8	1·5	2·3	—	164	2·9	Cleared—slight jar
54	13·2	7 500	99 000	7	1·2	2·0	—	248	3·3	Cleared—slight jar, slight gas
55	13·2	10 000	132 000	8	1·3	2·0	—	232	3·3	Cleared—slight gas
56	13·2	13 000	171 600	7	1·2	2·3	—	356	2·9	Cleared—slight gas, moderate jar
57	13·2	11 000	145 000	7	2·2	4·0	—	—	1·65	Cleared—slight gas, moderate jar
58	7·5	18 000	135 000	7	1·3	2·5	—	376	1·5	Cleared—slight gas, moderate jar
59	7·5	19 000	142 500	6	1·9	3·8	—	488	0·98	Cleared—slight gas, heavy jar
60	7·5	19 000	142 500	8	1·2	2·0	—	240	1·87	Cleared—slight gas, heavy jar
61	7·5	18 000	135 000	6	1·0	1·8	—	224	2·18	Cleared—slight gas, heavy jar
62	7·5	17 000	127 500	8	1·8	4·0	—	284	0·94	Cleared—moderate gas, heavy jar
63	3·81	29 000	110 490	7	1·3	3·0	—	500 +	0·64	Cleared—moderate gas, heavy jar
64	3·81	32 000	121 920	4	0·7	2·0	—	500 +	0·95	Cleared—moderate gas, heavy jar

arcing had taken place between the moving contact and the steel studs used to hold in position the plates forming the contact shroud. The ends of these studs had been completely insulated in the first place, but it was evident from this test that the insulation was insufficient. For the second series of tests, Nos. 38 to 64 in Table 5, the steel studs were as a temporary expedient replaced by fibre studs, and when this difficulty had been removed the breaker withstood 26 shots without showing any sign of distress. On examination after Test No. 64 it was found that both contact shrouds had been blown off, owing to the failure of the fibre studs. Practically all the studs had failed in tension, and their failure cannot be considered surprising in view of the very high current interrupted for a 66-kV circuit breaker.

(8) Conclusions.

It may fairly be claimed that the art of arc rupture in oil has made a marked advance in the past two or three years.

The use of a shrouded contact offers very considerable advantage over the earlier types of circuit breaker, in obtaining shorter arcing time, less indication of distress, and more consistent results.

Instrument equipment is available for obtaining adequate and accurate information from short-circuit tests.

When the rated breaking capacity which it is desired to prove is beyond the kVA capacity of the test plant available, an oil circuit-breaker with shrouded contacts can be tested successively to prove its suitability to handle high voltage and high current separately, and the combined results of such tests may be regarded as a guide to its behaviour under full-capacity conditions.

Finally, the authors wish to place on record their appreciation of the valuable co-operation of their colleagues in the preparation of this paper, and to mention in particular Mr. P. G. Ashley, B.Sc.(Eng.), Associate Member, Mr. A. Bannister, B.Sc.(Eng.), Associate Member, Mr. B. G. Churcher, Member, Mr. D. R. Davies, Associate Member, and Mr. A. C. Ehrenberg, Dip. Tech., Switzerland; also to express their thanks to the Metropolitan-Vickers Electrical Co. for permission to publish certain of the data.

APPENDIX.

Calibration of Measuring Apparatus.

(a) The Oscillograph.

The sensitivity of the voltage element is obtained from the formula

$$E = \frac{dRQ}{S} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where E = instantaneous potential difference applied to the series resistance R,
d = deflection of the oscillograph element, in millimetres,
Q = ratio of the voltage transformer,
S = sensitivity of the oscillograph element, in millimetres deflection per ampere.

The sensitivity of the current element is obtained from the formula

$$i = \frac{d}{S}\left(1 + \frac{R}{R_s}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where i = instantaneous current in the main circuit, in amperes,
R = resistance in series with the oscillograph element,
R_s = resistance of the non-inductive shunt.

In practice S is determined for each element by reading the deflection on the ground-glass screen previously mentioned and measuring the current by a precision milliammeter, a supply being obtained from a battery. An arrangement of switches and resistors enables this to be carried out at any time without disturbing connections or other adjustments. The mean of forward and reverse readings (which should always agree closely) is taken and by this means S is determined to within 1 per cent. In important tests R, which is seldom less than 10 ohms, is measured by a Wheatstone bridge, so as to include the resistances of all leads up to the potential terminals of the shunt. R is known to a few parts in 1 000. The main-current non-inductive shunts are of the concentric-cylinder, oil-immersed type. These are specially constructed to withstand the large mechanical forces which may be set up with currents of the order of 100 000 amperes, and may have various values down to 0·00005 ohm. They are checked periodically against primary resistance standards, and the resistance values are known to within 1 part in 1 000. The accuracy of overall calibration is therefore well within 2 per cent, which is adequate for tests of this kind.

With regard to other possible sources of error, inductive effects have been carefully considered. The residual inductances of the element series resistors have been made entirely negligible for frequencies up to 2 000 cycles per second by adopting a suitable construction. The residual inductances of the shunts are known and are too small to produce any observable effect in current records. The disposition of all leads, both in the laboratory and those running to the main circuits, is such that self-inductance and also mutual inductance with neighbouring power circuits is negligible. The natural frequency of the permanent-magnet elements is 3 000 cycles per second, and they will record quantities up to a frequency of 2 500 without appreciable error.

The calibration of the power elements is carried out on the same general lines, the deflection being noted when known direct currents are flowing in the electromagnet winding and the strip. It is beyond the scope of this paper to do more than enumerate the sources of error associated with these elements which have received attention. These are: natural frequency limitations, saturation of the electromagnet, phase-angle errors due to hysteresis in the electromagnet and to the inductance of the electromagnet winding, the main current shunt, the series resistors, and the phase angle of the voltage transformer, if used.

(b) The Pressure-Measuring Device.

The pressure device is coupled to a pressure gauge and a hand pump by means of an adaptor. With the

electrical connections shown in Fig. 10 the high-frequency voltage is set to the required value as determined by the voltmeter V, for example 2·5 volts.

Different static oil-pressures are then applied by means of the hand pump, and corresponding deflections are observed on the pressure gauge and the oscillograph.

The calibration factor, expressed as lb. per sq. in. per cm oscillograph deflection, has by this means been shown to be constant up to 300 lb. per sq. in.

Adjustment of the sensitivity of the apparatus may be obtained by varying the high-frequency voltage applied to the bridge.

DISCUSSION BEFORE THE INSTITUTION, 17TH MARCH, 1932, ON THE PAPERS BY MESSRS. KAPP AND CARROTHERS (SEE PAGE 685), AND MESSRS. PEARCE AND EVANS (SEE PAGE 703).

Dr. C. C. Garrard: The description by Messrs. Kapp and Carrothers of the various errors and limitations of the protection afforded by distance relays may be briefly expressed by saying that under all conditions the crossing of calibration curves of relays in series must be avoided. It is suggested, however, that they should cross in order that one relay may act as a back-up to another. Is this back-up action really necessary? As time-element overload relays are generally used as back-up, I think the additional back-up of the distance relays might be dispensed with. I am pleading here for greater simplicity, as relay systems tend to become so complicated as to defeat their own ends. In Fig. 2, if the lines (1, 2) went virtually upwards to infinity there could be no possibility of crossing. This, however, would leave a length of the line (near B_0) unprotected by the distance relay. The question is, how near can we bring the point 1 to B_0? In order to make sure that the whole of A_0B_0 is protected, let us assume that the point 1 is slightly beyond B_0 in the length B_0C_0. This means that faults very near B_0 in B_0C_0 would clear at A_0 also. There would thus be a certain percentage of false operations; by the law of averages this would be the same as the ratio of the distance 1 is beyond B_0 to the length of B_0C_0. Is it possible that the percentage of false operations under these conditions would not be greater than with characteristics such as those in Fig. 3? If this result could be attained, one would have the great advantage that the large percentage of faults would be cleared in the minimum time of, say, 0·4 sec., instead of between 0·4 and 1·5 or 2 sec. Further, the whole relay system would be vastly simplified, as the clock mechanism would be discarded. I cannot quite follow the argument immediately under Fig. 2, and on page 686 it is stated that the characteristic becomes flat again from point 4 onwards. This does not agree with Fig. 2, and if this portion of the characteristic were flat would not discrimination be seriously affected on distant faults? I should be glad if the authors would amplify the statement (page 689) that a distant small fault will bring the voltage down to a very low value. I do not think they have given sufficient weight to the effect of arc resistance (page 695). If this entirely swamps the impedance of the line, it seems to me that it will render the impedance form of protection altogether inadmissible. I should be glad if the authors would give some information with regard to the connection of the potential element of the phase-fault directional distance relays. In the case of directional relays for generator protection I believe it is best to connect the voltage coils to the leading phase: is this procedure also the best for distance relays? In my opinion the duplex protective apparatus shown in Fig. 14 is the best form of pilot-wire protection hitherto produced. It has the advantage that a single cheap pilot circuit can be used. Alternatively, telephone circuits hired from the Post Office can be used as pilots. The resistance of these circuits is apt to vary, as the Post Office retain the right to change the length of the circuit from time to time. The duplex system is, however, unaffected by wide variations in pilot-wire resistance. With regard to Part 3, I am doubtful whether a protective system employing the symmetrical components of the current will be of advantage except in special cases. By using relays which respond to the symmetrical components of the current, we really compare the sizes and angular displacements of the currents in the three phases; these have in turn to be compared, via the pilot wire, with the phase currents at the other end of the line. Further, I think that with all protective gear it is the current and potential transformers which cause the greatest inaccuracies. With the symmetrical-components system the magnetic circuits of the filters are likely to cause in addition yet greater inaccuracies; while there is no doubt that this method offers a great field for invention, I do not believe that the perfect system will be achieved on these lines.

With regard to the paper by Messrs. Pearce and Evans, I think it may be of historical interest to say that the first invention of an oil-blast circuit breaker was made nearly 30 years ago by the late Dr. Ferranti. The moving contact consisted of a cylinder, one end of which was smaller than the other; this portion fitted into the fixed contact, and the whole was immersed in oil. When the switch was operated the cylinder moved and compressed the oil inside it, which was thus forced out between the parting contacts. The device was precisely similar in principle to some recent inventions. Another of Ferranti's inventions, which is also mentioned in this paper, was the multi-break oil switch. The authors explain that the more intimately the oil is brought into contact with the arc, the better does the oil circuit-breaker function. This is really all that the oil-blast circuit breaker does. From this point of view, in a round-tank circuit breaker if there are only two breaks per phase it is obvious that a large proportion of the oil in the tank will be nowhere near the two arcs. If four breaks equally spaced around the tank are used, it is clear that a much larger proportion of the oil mass is active in extinguishing the arc. Although it might be thought that the argument could be continued and proportionately better results obtained with six or eight breaks, a point is soon reached when the individual arcs affect one another and counteract the improvement brought about by the larger number. Further, the

greater mechanical complexity has a bad effect by reducing the clearances. Hence, for voltages of 66 kV and above, while four breaks per pole are certainly better than two, it becomes questionable whether an increase above four is worth while. Eight or more breaks per pole would be decidedly a disadvantage. The question of round versus square tanks is primarily one of mechanical strength; a given degree of strength can be attained in either type by suitable design. Further, it is necessary to utilize the space available to the best advantage, i.e. so as to secure the maximum possible clearance between phases. From this point of view, if the three phases are placed in one tank, a rectangular form is preferable. If each phase is in a separate tank the circular shape is better. The evidence given in this paper shows that the cross-jet explosion pot gives excellent results. The point I would like to raise is, is this device worth while? It is an excellent principle of engineering that of two solutions, the simpler one is the better. In this connection there is a rather illuminating remark at the top of the left-hand column of page 720. The construction shown in Fig. 4 is excessively complicated. The requirement has been laid down that it should be possible to examine the contacts of an oil circuit-breaker by means of a periscope. It would require a very special kind of periscope to examine this contact. After a few operations the whole of the interior of the pot must become coated with more or less conducting deposits, and in view of the difficulty it would probably never be cleaned. In my experience most switchgear difficulties are due to minor troubles, and the best precaution against these is regular inspection and proper maintenance. In practice, circuit breakers made by reputable manufacturers and suitably installed do not fail under short-circuit conditions, even if they are fitted with plain breaks. Before we can accept the necessity of the construction advocated by the authors, it must be shown that for a given rupturing capacity it is possible by it to make a circuit breaker smaller in overall dimensions, and therefore cheaper, than the simpler design. I would point out that on the 132-kV " grid " lines the explosion-pot circuit breakers are just as big as the plain multi-break type. I am surprised at the statement on page 709 that contact is improved by burning, due to impurities being burned away from the surface. While it is true that butt contacts have had a considerable vogue in America, they are rightly viewed with disfavour by British engineers. The criterion of contact is, I think, the specific pressure per square inch of the parts actually in contact. With increasing pressure, the conductivity goes up asymptotically to a limit; pressures above this limiting value do not improve the contact. There is a contact-resistance film which is broken down at a certain pressure; hence the advantage of the line contact. The available total force is concentrated in a small area, so that the specific pressure per square inch is increased. If the area of contact is large, with the same total force the specific pressure is less and the contact worse. On the other hand, if a point contact is adopted the specific pressure may be very much above the value given by the asymptote to the conductivity/pressure curve, and a good deal of the pressure is wasted. In my opinion, therefore, the reason why burning causes an improvement of the butt contacts is that it converts them into line contacts. In conclusion, I should like to refer to the question of recovery voltage. On page 715 it is stated that the rate of rise of recovery voltage is not at present seriously considered in the classification of circuit-breaker performance, and I think that this is to be regretted from the point of view of the theory of the subject. It is in the variation of the speed of rise of recovery voltage that an explanation of many of the at present inconsistent experimental results will probably be found.

Mr. E. B. Wedmore: The success of discriminating relays depends upon the reliability of operation of the circuit breakers; hence the importance of reliability stressed by Messrs. Pearce and Evans. Further, the service is greatly improved if the circuit breakers can be made to operate quickly. In several foreign countries large testing plants have been installed for the development and testing of circuit breakers, and the experience gained from the use of these plants has resulted in the production of new designs of circuit breakers which promise a solution to some of the difficulties associated with the older types. I welcome the paper by Messrs. Pearce and Evans because it contains the first published description of a circuit breaker made by a British manufacturer based on the new ideas and principles that are being developed by recent research. Where a circuit breaker develops its own circuit-breaking force, it is essential that tests on every feature of the design should be made over the whole range of possible working currents. Tables 1 to 5 are a mere sample of the extensive series of tests required for the effective commercial development of a circuit breaker of the type in question. If we are to be able to deal effectively with the needs of the industry and ascertain with reasonable precision the proper rating of British designs, and if we are to maintain our position in the race—now becoming very rapid —for securing the market for new designs, it is essential that we should have the testing facilities to which the authors refer on page 712. It is clear that the designers do not pretend that they have solved the problem of introducing an oil seal between the contacts. Experimental models in which oil is effectively introduced between the contacts show a voltage drop of the order of 100 000 volts per inch, and similar figures may be expected to be realized in practice. The values given by the authors do not approach that figure, for in the K5 design only a turbulent mixture of oil and gas is introduced into the gap. There is no difficulty in getting turbulence. The designers would have been faced with a difficult problem had their object been to avoid turbulence. The authors claim to throw an oil jet across the arc gap. As the amount of oil is fixed but the amount of gas will vary over an immense range, I doubt whether it is possible to obtain the necessary nice combination of gas action and oil action over any considerable range of working conditions. The circuit should be broken at the first current zero after the circuit-breaker contacts have separated, or at most within, say, one cycle, and this involves a very rapid acceleration of the oil. As the gas is very light in comparison with the oil it will seek the nearest exit via the path involving the

minimum displacement of oil. A bubble of gas is formed which at heavy currents creates a very high pressure inside the chamber, and the gas stream will carry oil vapour and oil with it. The result is that the blast is continued after the current has passed the zero value, and the material which is then being carried forward last of all is much cooler than that in the arc stream. I feel that the authors' design is valuable because the arc is extinguished in a small chamber readily made capable of withstanding the high pressures set up when heavy currents are broken. This form of switch need not have the large dimensions and substantial tank construction necessary in the more elementary designs which now dominate the market. The authors do not make a comparison between the results obtained with their design and with the common type, though I anticipate that by fitting their device they will be able easily to double or treble the rupturing capacity of an ordinary circuit breaker. I anticipate that the rupturing capacity would be further increased, however, by venting the first chamber so as to allow a readier egress of gas, than by using the pressure first developed to create motion of the oil. The baffle construction is valuable, for it controls and prevents extension of the arc when the current is heavy, besides reducing the amount of burning of contacts. The oil film should protect the insulating material from serious destructive action.

Mr. T. Carter: I shall deal first with the paper by Messrs. Kapp and Carrothers. Until the advent of the British " grid," little use was made in Great Britain of time-distance protection, and it is because of what the authors, amongst others, have done that British manufacturers have been encouraged to develop protective systems of this type, which are now in extensive use on the grid. Fig. 1 shows the characteristics of Continental and American practice prior to the British development, and many impedance relays are working on the lines there indicated. The demand for something better for the grid led, however, to the development, in the ratio-balance protective system, of characteristics like those shown in Fig. 2. The desirability of instantaneous tripping, and of characteristics that would avoid crossing, was pointed out by Mr. Leeson* at the 1929 Paris E.H.T. Conference, and the details were fully described by Mr. Leeson and Mr. Leben in a paper† presented to the 1931 Conference. The qualities of distance protection having such characteristics approach those of Merz-Price protection. It is always necessary, however, that time-delays should be tolerated for faults at some points with distance protection; and it seems to me, therefore, that Merz-Price systems are the technical ideal. It is only the cost of pilots that prevents their use on the grid for long lines. Many short sections are protected by, for example, the split-pilot system, which is of the Merz-Price class. The authors appear rather to underrate the effect of arc resistance on the correct operation of distance protection. It is clear that, whether the effect is great, or whether it is small, it can be eliminated altogether by making the basis of the system a reactance measurement, and not an impedance measurement. I think it best to avoid the use of compensated voltage whenever possible; but if it has to be used it is not disadvantageous, as the authors suggest, for reactance relays, because a comparatively large phase-angle error gives a very small error in reactance measurement. I agree with what the authors say about supplying distance relays on systems like the British grid with leakage current alone; but, when operation is by means of current in the earthed phase, the error is small in practice; and this is borne out by what is said in the paper near the top of page 694. It is therefore better to operate by current in the earthed phase than to use the authors' method (Fig. 10), which further complicates something already inherently complex. I agree that protection is more difficult when there is a neutral earthing resistance of high value than when there is solid earthing; but I suggest that the usual high-voltage network, earthed through a resistance of medium value, is easier to protect than if the system is solidly earthed, because, for example, the relays have to discriminate over a smaller range of current. The duplex system with pilots tends to reduce clearance times; but this is offset by the need for a balanced pilot-circuit; and the system does not allow an interlocking signal to be transmitted by one superimposed high-frequency current in the overhead line. On the other hand, the interlock system has only a plain pilot, and uses a simple signal. It is thus eminently suitable for working with superimposed current, and is actually in use in this way. The suggestion for a " pilot earth-wire " (page 699) is very ingenious, and I should like to know whether it has actually been used, and, if so, how it behaves in service, particularly in respect of durability. I agree, in view of the vital part that protective systems play in maintaining continuity of supply, that a large margin of stability is desirable; and I consider that all protective systems should have this characteristic stated in the form of a stability factor. Mr. Clothier has asked me to make the suggestion that, in view of the importance of infallibility of operation in protective systems, the Institution might well undertake a special study of such systems, and that for this purpose it might set up a special committee, which would report to it annually, but the scope of its annual reports would be wider than that of the Progress Reviews printed in the *Journal* from time to time. The committee should consist of consultants and users, to the exclusion of manufacturers, who could, however, put at its disposal a large amount of helpful information.

The testing of circuit breakers is the only right way to judge their performance, and the paper by Messrs. Pearce and Evans will further stimulate the realization, already becoming general, of the value of facilities for conducting British short-circuit tests. To be fully useful, these must be made under some agreed standard test-circuit conditions of severity, since otherwise it is difficult to asses in any completely useful way, in relation to selection of circuit breakers, the value of tests made, on the one hand, with plant of definitely known characteristics operating in a known circuit, and those made, on the other hand, with borrowed

* Report of the International Conference on Large Electric Systems, 1929, vol. 3, p. 587.

† H. H. LEESON and H. LEBEN: "The Principles of Feeder Protection and their Application to Three Modern Systems," Report of the International Conference on Large Electric Systems, 1931, vol. 2, p. 873.

plant of varying and uncertain constants. One of the authors' main endeavours seems to be to improve switching capacity by using special contacts; and the illustration in Fig. 4, together with the short-circuit tests reported in Section 7, relate to what appears to be their main line of attack on the problem. The paper indicates that much testing is required to establish whether such special devices are or are not of general benefit; I find it difficult, indeed, to discover precisely how much improvement in switching capacity the authors claim to have derived from the use of the cross-jet explosion-pot contact over the behaviour normally observed in circuit breakers with plain contacts. Shrouded contact devices appear to give good performance within the range where there is no distortion or deterioration of the components of, and in, the shroud, and repeated tests have shown that better performances can be obtained than with plain contacts without stressing tank enclosures more severely; but, beyond the stage where distortion or deterioration begins, the performance of circuit breakers with shrouded contacts may become critical earlier than it does with plain contacts. On page 707 the authors state that the pressure generated in chamber " a " is communicated to chamber " b " through the opening " f," and that this causes " a leakage of oil through the horizontal passages." It is not clear to me how this action takes place. The pressure exerted on the oil in " b " through the hole " f " would appear likely to be opposed by a pressure originating at the same point as the one acting through " f," but operating first horizontally to the left of the moving contact along the passages " cc," and then vertically upwards through the hole in the bottom of " b." Does not this mean that since the pressure at " f " is opposed by the last-mentioned pressure there will really be very little movement of oil out of " b "? On page 711, dealing with the rate of rise of recovery voltage, the authors state that the voltage is " applied " by the sudden removal of the short-circuit current. Is the word " applied " strictly correct? Should not the term " allowed to grow " be used instead? It is also not clear to me how, in the circumstances contemplated, the voltage proves " particularly inconvenient " at the contacts. The inconvenience at contacts is normally caused by current, and not by voltage, and, since the voltage is greatest at the zero pause of the current, and rises to its highest value when the current has finally ceased, it does not seem to be necessary to regard it as an inconvenience at the contacts. It may be inconvenient if it causes a flash-over to some abnormal part of the circuit-breaker structure; but not otherwise, except so far as its rate of rise at each zero pause is a factor tending to establish another half-wave of current. I consider that the authors speak rather loosely of inconvenience when the performance is over, the current having been finally interrupted. Fig. 6 would be much more useful if numerical values were given to indicate more definitely the relations between the variables. It is not clear whether " inches " refers to break, or to travel; nor is it obvious what inches of arc duration actually are. According to the Table on page 714, showing the allocation of oscillograph elements, only one voltage was measured; and this is confirmed by the record of only one voltage in each test in Tables 1 to 3. It would be interesting to know how the 3-phase kVA calculated on recovery volts was arrived at in these tables, when the recovery voltage of one phase only was known. The values of the duration of the arc in half-cycles recorded in Tables 1 to 3 are not essentially different from those usually obtained with plain contacts; and it is for this kind of reason that I should like to have some further information about the amount of benefit in switching capacity obtained from the use of the authors' special contacts. On the showing of the

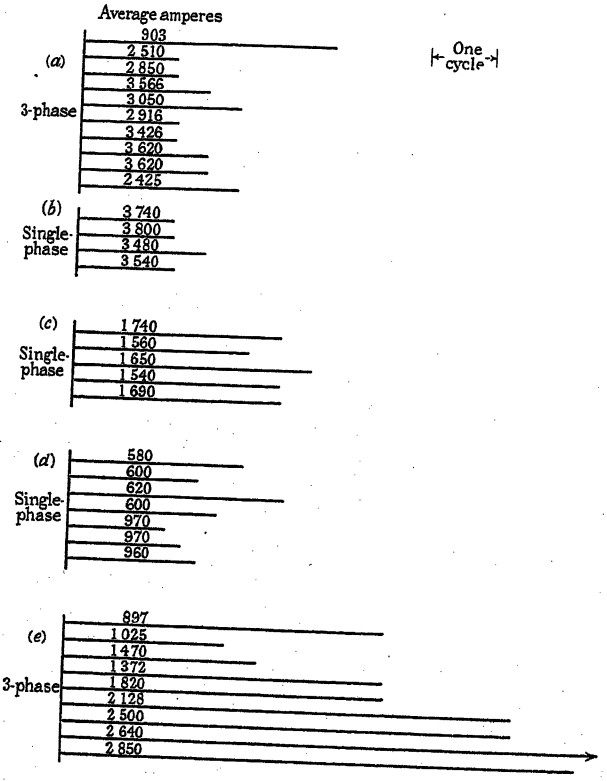


FIG. A.—Comparison of arcing times.

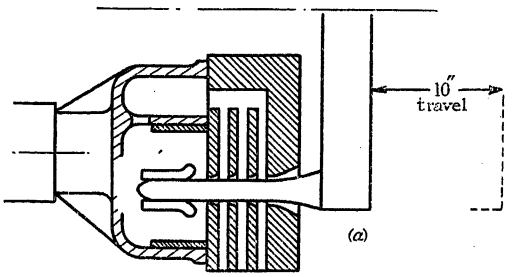
(*a*) and (*b*) De-ion grid on type G. 2 circuit breaker, at 110 kV. Contact speed at rupture, 5 ft. per sec.*
(*c*) Oil-blast explosion-pot on type FHKO–139–54B circuit breaker, at 110 kV. No-load speed, 7·8 ft. per sec.†
(*d*) Cross-jet explosion-pot on type FHKO–139–54B circuit breaker, at 96 kV.‡
(*e*) Plain butt on type G. 11 circuit breaker, at 115 kV.§

* L. W. DYER: *Electrical World*, 1930, vol. 95, p. 786.
† D. C. PRINCE and W. F. SKEATS: *Transactions of the American I.E.E.*, 1931, vol. 50, p. 506.
‡ H. PEARCE and T. T. EVANS (see p. 703).
§ J. B. MACNEILL: *Transactions of the American I.E.E.*, 1924, vol. 43, p. 629.

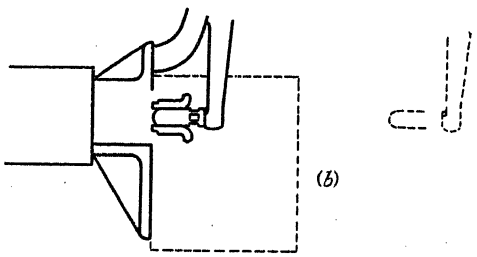
figures, these contacts do not seem to be worth the additional complication they necessarily introduce. With regard to Table 3, I should be interested to know whether tests were made at kVA values well above the rating of the circuit breaker used. I have not been able to find any definite statement of the normal rating of this circuit breaker; but the tank capacity is 100 gallons, and such a tank is usually associated with a breaking capacity of about 500 000 kVA. What kVA benefit is actually afforded by fitting the explosion pot to such a circuit breaker? The values given in Table 1 are 535 000 kVA, calculated on line volts, and 430 000 kVA, calculated on

recovery volts. The former is only 7 per cent above the value I have assumed to be the rating of the K5 circuit-breaker, and the latter is actually below it. It seems to me that tests at values definitely above the normal rating are essential in order to indicate the factor of safety implied in the rating, and that particulars should be given of the conditions of severity in the test circuit, the self-capacitance, and the rate of rise of the restriking voltage.

Mr. W. A. Coates: In connection with the paper by Messrs. Pearce and Evans, Fig. A illustrates the trend



Test №	Arc length	Initial kV	Arc half-cycles	Average current amperes	3-phase kVA recovery basis	Cushion lb. per sq. in.
104		12·5	2·8	3 380	62 000	None
105		27·0	1·4	7 250	242 000	12
106		28·9	1·4	9 000	386 000	6
107		13·0	2·4	3 370	63 000	None
108		31·4	2·0	10 700	48 000	41
109		25·9	2·0	7 870	302 000	12
110		31·6	1·4	10 500	480 000	17



111	12·7	2·6	3 980	77 000	None
112	26·0	2·7	7 480	280 000	None
113	31·6	4·1	10 000	440 000	35

Tests on Snap Break in Standard Switch.

101	12·1	3·5	4·920	86 000	35
102	27·5	4·1	7·600	278 000	No record
103	31·7	6·0	9·830	440 000	140

FIG. B.

(a) Type K. 4a with cross-jet explosion-pot.
(b) Type K. 4a with de-ion grid.
} Scale = ⅛.

of advance in circuit-breaker design. The length of the horizontal line indicates the arcing times which have been claimed by different writers for their own types of circuit breakers in various papers presented recently. It will be noted that with the ordinary plain break, the arcing time is both long and very variable. All the three well-known types of special-contact circuit breakers show greatly reduced arcing times. It may be felt that these results are not strictly comparable because they concern different types of circuit breakers. Fig. B shows the results of a limited series of tests taken with different contacts fitted in the same circuit breaker. They therefore bear direct comparison, and again it will be seen that the arcing times with the shrouded contacts are the shortest and most consistent. The authors are to be congratulated on the fact that they have been able to use equipment which gives on a single film a synchronized record of movements and pressure, as well as of amperes, volts, and watts. In particular, the pressure record is much more accurately readable than those available hitherto, and it has enabled us to prove a theory that had been held for some time previously, that in an oil circuit-breaker the pressure waves which are set up are irregular in relation to the current wave, and that the arc finally goes out at the instant when the peak of the pressure wave synchronizes with a zero pause in the current wave. This is clearly shown in Fig. C (page 726), which indicates in the upper portion the path of contact through the " grid " of a cross-jet explosion-pot, while plotted below are the pressure and current waves. This graph was built up from the oscillogram of a definite test.

Dr. W. B. Whitney: I congratulate Messrs. Pearce and Evans on their achievement in obtaining nine such clear records on one film (see Fig. 12). On page 718 the authors state that the arc energy was too small to be measured; an arc energy of from 25 to 50 kW-sec. per phase is, however, shown in Fig. 12. It would be interesting to know the lowest arc energy that could have been read on the records to which they refer. With regard to the behaviour of the shrouded contact at different circuits, one would expect that the contact shown in Fig. 4 would give fairly consistent behaviour on heavy currents, but that the consistency of the results would be less at reduced currents when the clearance outlets around the moving electrode would allow a greater proportion of the arc products to escape in directions other than across the arc path. Some such inconsistency is in fact shown for currents below 1 000 amperes in Tests 35 and 36, Table 4, and Tests 46 and 47, Table 5, where there are variations of nearly 1 to 2·5 and 1 to 1·7 in arc duration, or (from the figures of arc length and arc duration) estimated variations in arc energy of 1 to 10 and 1 to 3·5 respectively. In the absence of information as to the length of stroke within the shroud, it is not clear whether the associated variation in length takes place within the shroud or is due to the contact moved out of it, and information on this point would be of interest.

Mr. J. W. Rissik: We seem to be paying too much attention at present to the question how we can improve the existing oil-circuit breaker, whereas developments abroad show that foreign engineers are experimenting with other types of circuit breakers. We must consider whether the oil-less circuit-breaker is destined eventually to displace the oil circuit-breaker, just as the rectifier displaced the rotary convertor or the recipro-

cating engine was displaced by the turbine. In this connection I notice that on page 707 reference is made to the work of Dr. Kesselring, who has followed the scientific method of first proposing a theory of the circuit breaker and afterwards designing a switch to fit in with it, instead of following the old method of basing the design on empiricism. The success with which his circuit breaker has met shows that his theory cannot be far wrong. The female contact is similar to that used in the orthodox circuit breaker and is enclosed in an expansion chamber resembling an explosion pot. The theory is that in order to obtain a successful switch we must aim at de-ionizing the arc space, i.e. neutralizing all the free electrons of the arc before the recovery voltage reaches a definite value. When the male contact leaves the female contact, and whilst it is still inside the nozzle, the arc generated will cause superheated steam to be formed. As soon as the male contact leaves the nozzle, the steam will expand. Kesselring has shown that if we allow the steam to expand freely there is such a rapid temperature-drop that it becomes saturated before the recovery voltage has had time to build up to the value necessary to restrike the arc. The idea of obtaining saturated steam had its origin in the fact that in a superheated vapour the molecules constituting the gas are relatively far apart and therefore any negative electrons left behind by the arc can move freely in the large spaces between the large molecules, by reason of their being outside the radius of attraction of each molecule. If, however, the molecules are packed more closely together, every free electron will be attracted by one or other of the large molecules and immediately neutralized. Thus, if on breaking the arc a saturated vapour is formed, de-ionization immediately occurs and the arc is quenched. It is for this reason that the circuit breaker is called the " expansion breaker " and gives arc-free rupture under normal operating conditions.

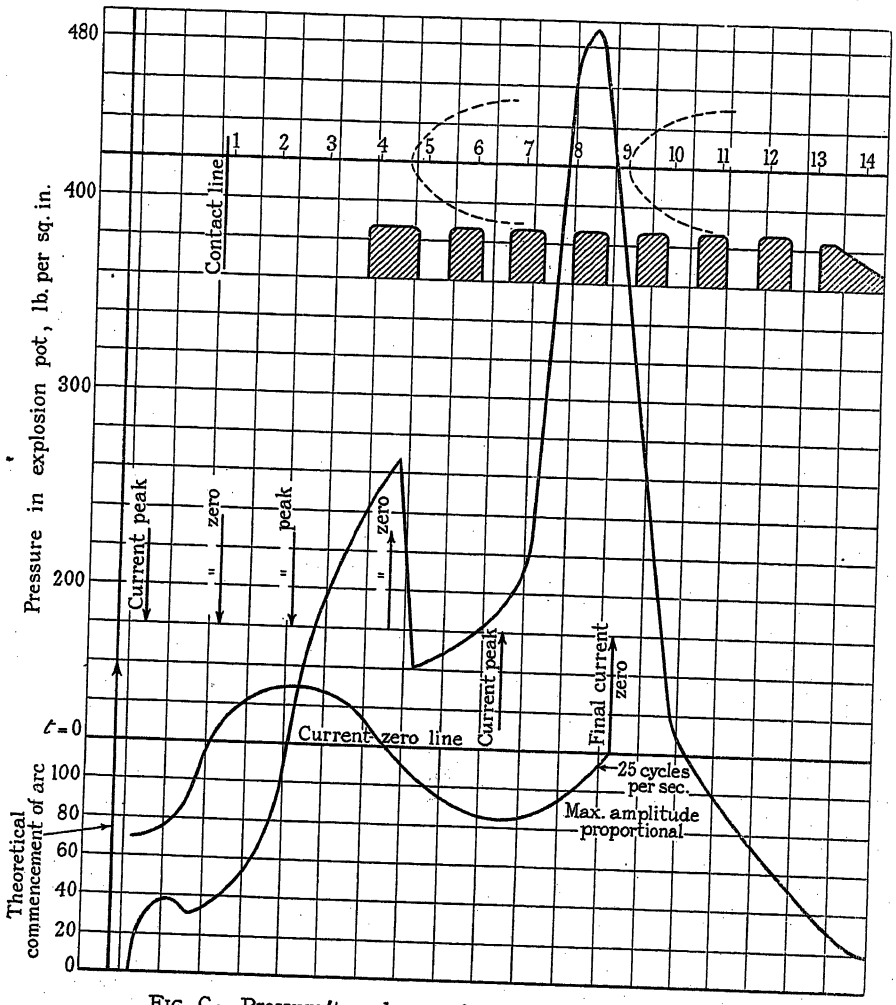


FIG. C.—Pressure/travel curve for cross-jet explosion-pot.

Prof. J. K. Catterson-Smith (*communicated*): I am particularly interested in Part 3 of the paper by Messrs. Kapp and Carrothers, where the authors discuss the possibility of making use of the distortion of the vector currents and voltages for the purpose of operating relays. Their method is based on the symmetrical-component analysis due to Mr. C. Le Geyt Fortescue which is often used for the treatment of short-circuit problems as well as of the problems dealt with in the

paper, especially in the United States. As a number of difficulties are encountered when making such calculations, however, there is much to be said in favour of the more ordinary and better-known graphical methods employed in this country. For instance, when using the symmetrical-component treatment it becomes necessary to settle the values—even if only approximately—of the positive, negative, and zero phase-sequence reactances of the generator, transformer, and line circuits. The zero phase-sequence circuit for earthed systems involves a knowledge of the penetration of the earth current to a depth of, say, 5 000 ft. below the surface, and thus there are a number of somewhat complicated networks to be solved when attempting the calculations referred to above. For many cases it seems to be simpler to find the displacement of the neutral of the system, treated as a floating neutral, and then—using the value and phase of the distortion voltage so obtained—to take the earth current as this displacement voltage divided by the impedance of the line circuits in parallel plus the earth-circuit impedance. A number of experimenters have endeavoured to use the distortion of the voltage diagram for relay working, but I understand that the operation of this type of system is rather critical and more suitable for the laboratory than for practice. Nevertheless, the method should be explored, as it appears to offer many useful applications.

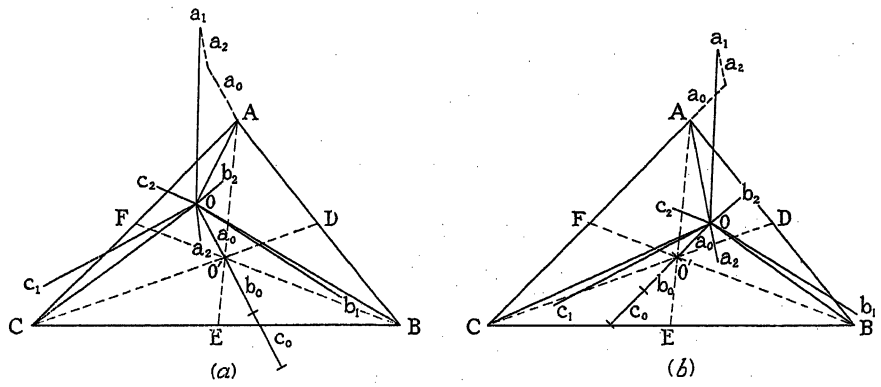


FIG. D.

OA, OB, OC.—Line-to-earth voltages.
O'A, O'B, O'C.—Line-to-neutral voltages.
a_1, b_1, c_1.—Positive-sequence components.
a_2, b_2, c_2.—Negative-sequence components.
a_0, b_0, c_0.—Zero-sequence components.

Mr. D. Jamieson (*communicated*): Messrs. Kapp and Carrothers deal with the question of symmetrical components (page 700) in a very general way, leaving out any attempt at a mathematical analysis. When, however, they refer to neutral displacements it is not immediately evident what they mean. One could assume, for instance, that where a voltage triangle is distorted there must be a neutral displacement. This raises the question what is the actual neutral, and, if there is a displacement, where is the true neutral from which the actual neutral is displaced. The vector sum of the voltages from the centroid to the apexes of any triangle is zero, and the centroid may therefore be defined as the true neutral. Thus if we have a triangle whose sides represent the line-to-line voltages of a system, the true neutral of the system is at the centroid of the triangle. If the system has an earthed neutral, there is another point in the triangle which represents earth potential, and the vectors from this point to the apexes of the triangle represent the line-to-earth voltages. If there is no current flowing in the earth at the point of measurement, the earth-potential point coincides with the centroid, however distorted the triangle may be, since the vector sum of the line-to-neutral voltages must be zero. When, however, current does flow in the earth, the earth-potential point no longer coincides with the centroid of the triangle; but the vector joining it to the centroid of the triangle (which, I think, is the "displacement vector" referred to by the authors) represents in magnitude and direction the zero-sequence component of the line-to-earth voltages. Fig. D shows this at a glance and illustrates very plainly the value of the conception of symmetrical components in forming a picture of the effect of the earth current on the voltages. In Fig. D, (*a*) and (*b*) represent the same voltage triangle (an unsymmetrical one, for generality), but the earth-potential point is different in each case. The line-to-earth voltages, OA, OB, OC, have been split up into their symmetrical components by geometrical construction. In each case the centroid is in the same position, the positive- and negative-sequence components are the same, but the zero-sequence component is different and in each case exactly equal to the distance between the earth-potential point and the centroid of the triangle. It is immediately evident, as the authors point out, that the zero-sequence component is the important quantity during earth faults. A potential transformer on the low-voltage side of a power transformer automatically produces a neutral which is at the centroid of the line-to-line voltage triangle, since the sum of the potential-transformer secondary voltages must be zero at the neutral. Hence if there is such a neutral displacement as that referred to by the authors, the line-to-earth voltages are not correctly reproduced unless some form of compensation is adopted. The authors state that the displacement voltage is either in phase or 180° out of phase with the earth or zero-sequence current. This statement would only be true if the zero-sequence impedance were entirely resistive. In the general case it is more likely to be almost wholly reactive, so that a compensating voltage derived from the zero-sequence current would require

to lead this current by approximately 90°. I would enter a plea for the abolition of the term " phase rotation " and the substitution of the term " phase sequence." Phase rotation is a physical property of rotating machines, and when the term is applied to static transformers or to any set of 3-phase terminals it can be very confusing, especially in connection with a vector diagram. On the other hand, " phase sequence " definitely conveys the meaning that the voltages reach their maximum values in a definite order or sequence. Such a sequence must be either "standard " or " non-standard," and this conveys its effect on rotating machines. The terms " positive sequence " and " negative sequence " are also preferable to " forward phase-rotation " and " reverse phase-rotation," and have the additional advantage of a meaning in symmetrical co-ordinates.

Dr. J. Kopeliowitch and **Mr. J. K. Brown** (*Switzerland; communicated*): On page 712 of the paper by Messrs. Pearce and Evans it is claimed that by means of two series of short-circuit tests one can check the performance of a circuit breaker in which the arc is controlled by means of a shroud. Firstly, a series of tests is made up to full voltage or over, to determine that the circuit breaker can withstand the required voltage when the minimum assistance is derived from the shrouds. Secondly, a series of tests is made ranging up to full current or over, at the maximum voltage. This method, which had been described* elsewhere before the present paper was read, may have dangerous consequences. It is clear that the arc is more easily extinguished at lower voltages, so that tests carried out with large currents and lower voltages are no criterion of what would take place at the full rupturing capacity. Circuit breakers with explosion chambers are, in general, sensitive to overloading. In order to produce the necessary blow-out effect on the arc, explosion chambers must work with high pressures. Every additional half-period of arcing causes an increase of the pressure in the explosion chamber, and it is essential to take this fact into consideration when tests are carried out on switches with reduced rupturing capacities. This conclusion is supported by the results of tests on a 24-kV 3-pole oil circuit-breaker equipped with explosion pots. The first series of tests was made with a recovery voltage of 11 kV and current values ranging from 3 000 to 10 800 amperes. The tests were then carried out with a recovery voltage of 24 kV; the lowest value of the current was 1 330 amperes, and with 6 150 amperes the limit—as determined from the pressure—was reached. This latter value corresponds to a 3-phase capacity of 255 000 kVA. According to the authors' proposal the maximum rupturing capacity of the circuit breaker—as derived from the tests at 11 kV—would be 450 000 kVA. In our opinion, in order to make quite sure of the performance of circuit breakers (particularly those with explosion pots), it is necessary to determine their behaviour under short-circuit conditions, i.e. at the full rated voltage and current. Tests on circuit breakers with plain breaks can in extreme cases be carried out with reduced rupturing capacities. Fig. E shows the relation between the pressure and the rupturing capacity for a 3-phase circuit breaker with all three phases in one tank; the tests were carried out with a recovery voltage equal to the normal rated voltage. It may be seen that when the first few points have been determined it is possible by extrapolation to find the maximum pressures for higher capacities. From these tests it is also possible to determine the relatively simple relation between the arc duration and current for the rated voltage, and consequently the production of gas and the pressure in the circuit breaker. As a result the various factors which determine the performance at full capacity can be calculated. When the circuit breakers are correctly designed this method of calculation gives very accurate results which agree with the values obtained from actual tests in the high-power test plant. In some cases, for example e.h.t. circuit breakers with larger rupturing capacities, this method is essential as the test-plant capacity available may be inadequate. With regard to short-circuit tests, particular attention should be devoted to the calculation of the kVA interrupted. We would emphasize the authors' statement (page 715) that " it is to be regretted that as yet there is no uni-

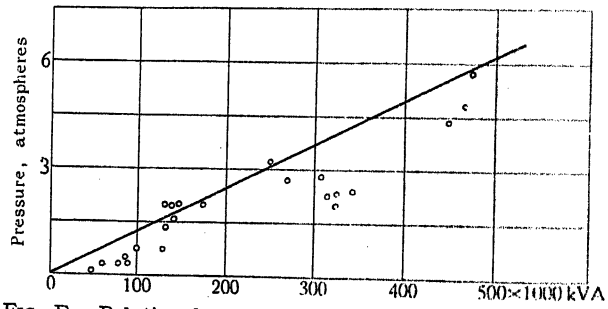


FIG. E.—Relation between pressure and 3-phase rupturing capacity for a 3-phase breaker with all three phases in one tank.

versally agreed method of calculating from test oscillograms the power broken." Until an international agreement is reached it will remain extremely difficult to make comparisons between the performance of circuit breakers under different short-circuit conditions. The main controversy is with regard to the current interrupted. All countries are in agreement that it should be calculated at the moment of separation of the contacts. Switzerland, France, Germany, Italy, and others, together with the I.E.C. Committee, consider the a.c. component (I_r) alone, while England and America include the d.c. component (I_c). These facts are hardly in agreement with the authors' statement (page 715) that the current factor is generally accepted as defined in B.S.S. No. 116—1929. According to page 25 of this Specification the current broken is given by

$$I_k = \sqrt{(I_c^2 + I_r^2)}$$

Fig. 12 of the authors' paper shows that for phase Y, I_r = 2 630 amperes, I_c = 2 900 amperes, and therefore I_k = 3 910 amperes. Thus $I_k/I_r = 1{\cdot}49$, and $I_c/I_r = 2\,900/2\,630 = 1{\cdot}11$. This value of I_c is considerably in excess of the permissible value (30 per cent of I_r) stated in the Minutes of the July 1930 Meeting of the I.E.C. Advisory Committee, No. 17, on Circuit Breakers

*F. Houst: Report of the International Conference on Large Electric Systems, 1931, vol. 1, p. 553.

(Clause 6). This makes the rupturing current in one phase 49 per cent too high The reason for neglecting the d.c. component of the current when calculating the rupturing capacity has been explained previously.* With regard to the voltage rating, it has become general practice in all countries to consider the recovery voltage after the short-circuit, the one exception at the moment being America. The proposal put forward by Germany to use the active voltage has not been accepted, as the V.D.E. Specifications definitely infer the recovery

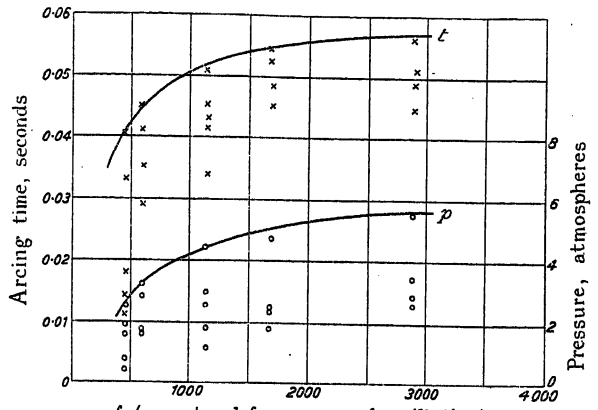


FIG. F.—Relation between arcing time (t), pressure (p), and natural frequency of oscillation (f_0) of test circuit.

voltage. This decision was probably reached on account of the difficulty of calculating the active voltage from the oscillograms of actual short-circuit tests. In the recent proposals of the I.E.C. it is recommended that the rating of circuit breakers should not be given in terms of kVA. If this idea is adopted tests should be carried out in such a way that the rated current is interrupted at a recovery voltage equal to the rated voltage of the circuit breaker, i.e. the recovery voltage for short-circuit tests should equal the rated voltage, and the voltage before the test should be somewhat higher to compensate for the decrement during the short-

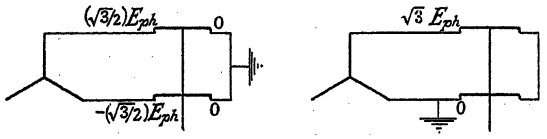


FIG. G.

circuit. Turning to section 4(g), concerning the number of breaks in series, it is difficult to understand the authors' statement on page 710 with regard to the non-uniform potential distribution across the breaks when the system is earthed. Although the voltage distribution for the three poles is different, this condition has to be met by all types of circuit breakers. In single-phase tests on a circuit breaker having four breaks in series for the two different conditions shown in Fig. G no difference of performance was observed as judged from the arcing times and the pressures in the breaker. A second series of tests on two breaks in series, with the neutral point earthed and unearthed, gave a similar result. The total voltage across the circuit breaker was the same in each case, the actual terminal voltage with respect to earth being as shown in Fig. H. For 3-phase tests similar distributions occur, so that it may be concluded that the exact difference due to the potential distribution for multi-break as opposed to 2-break switches cannot be derived from systematic tests.* With regard to recovery voltage (page 711), the authors state that anything which promotes a steep decrement curve is likely to encourage a corresponding rise of voltage when the short-circuit is removed. It may be remarked, however, that the voltage decrement during the short-circuit is only compensated after a time-interval of the general order of seconds, while the important feature is the transient oscillation occupying only several microseconds. Consequently, the reason why a machine with low reactance gives a high value of recovery voltage is the fact that the reduction in the reactance causes an increase in the natural frequency of oscillation. This fact is illustrated in Fig. F, which shows how a reduction of the natural frequency of transient oscillations affects the arc length and pressure. The tests were carried out on the Brown-Boveri high-power electrical testing plant, which had a natural frequency of

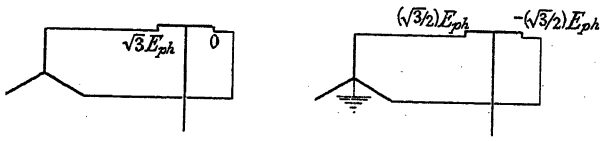


FIG. H.

6 800 for the connections used. The reduced stress on the circuit breaker is extremely important, and it is clear that the test conditions met with on a testing plant with a high natural frequency of the order of 25 000 are more severe than those encountered on a network where the natural frequency is considerably reduced owing to the additional electrostatic capacitance of the transmission lines.

Messrs. R. O. Kapp and **C. G. Carrothers** (*in reply*): Dr. Garrard wishes to know whether the back-up feature provided by impedance relays, as shown, for instance, in Fig. 2, is necessary if overload relays are employed instead as a back-up. In our opinion overload relays are not a desirable means of back-up for impedance protection, and they should be omitted on networks protected in this way. The overload is a non-discriminating back-up, whereas the back-up feature provided by the impedance relays themselves is discriminating. It ensures that if it comes into operation only two sections will be brought out, whereas back-up overload relays may bring out unnecessarily a great many sections. It is not at all necessary that the lines on the back-up portion of the impedance characteristics should cross; and if they do, it will be at a great distance from the protected section where crossing does not matter. Dr. Garrard also refers to our remark that the characteristics shown in Fig. 2 again become flat from point 4 onwards. The word "flat" is perhaps misleading, and it would have been

* J. KOPELIOWITCH: "International Standardization of Oil Circuit-Breakers: Definition of Rupturing Capacity," *Revue Générale de l'Électricité*, 1928, vol. 24, p. 625.

* This fact may be readily explained from physical considerations, as is shown in an article by Dr. J. Kopeliowitch which will be published shortly in the *S.E.V. Bulletin*.

better if we had said that they become " flatter." We agree with Dr. Garrard's suggestion that the small risk might be taken of false operation involved in covering a larger portion of the protected section by instantaneous protection; the point is interesting.

Dr. Garrard and Mr. Carter are of the opinion that arc resistance is important and that its effect should be eliminated from distance protection. Apart from the arguments set out in the paper, there is the experience of the impedance type of protection which does not go to support the contention that its operation is rendered unreliable by arc resistance. In our opinion the fear of the effect of arc resistance is likely, as time goes on, to diminish rather than increase.

We support Dr. Garrard's suggestion that it is generally desirable on directional relays to connect the potential coil to the leading phase. While we agree with him that the symmetrical components cannot be obtained with great accuracy, we should like to point out that a considerable inaccuracy does not matter when these components are used merely to operate directional relays. In such circumstances it is not important to have a correct quantitative indication of current or voltage, but it is very important to have as positive an indication as possible of the direction of power. The great advantage of the negative phase-sequence component is that it gives a very pronounced indication of the direction, particularly in proximity to the fault.

Mr. Carter inquires about the durability of the pilot earth-wire. Such a wire was installed on a portion of a line in Cheshire in May 1929, and repeated tests have been made to ascertain its condition. This is still good, and the experience so far gained suggests that there is no fear of deterioration or damage due to storms or other causes.

We fully agree with, and our experience confirms, the view put forward by Prof. Catterson-Smith that the use of distortion of the voltage diagram for relay working leads to rather over-sensitive operation.

We agree with Mr. Jamieson that the words " neutral displacement " are somewhat ambiguous, and we confirm that in the paper they mean the zero phase-sequence voltage. As Mr. Jamieson says, some form of compensation is necessary if a voltage taken from potential-transformer connections is employed as a measure of the zero phase-sequence voltage. The compensation may be for the drop in voltage due to the current carried by the power transformer and also for the displacement of the phases occasioned by the magnetic coupling in the transformers. The phase relationships which may occur with various power-transformer and potential-transformer connections, and which also depend on how the neutral point is earthed or whether it is unearthed, form a very large subject which would almost require a separate paper. Mr. Jamieson rightly points out that the wording is somewhat loose where we say in the paper that the displacement is either in phase, or 180° out of phase, with the zero phase-sequence current. We should have said that the current in the neutral due to the zero phase-sequence voltage is either in phase, or 180° out of phase, with the corresponding line current, but this current may bear any angular relationship to the zero phase-sequence voltage, this relationship being a function of the circuit constants. We agree with Mr. Jamieson that the term " phase rotation " might, with advantage, be dropped, and we would go further and suggest that the whole terminology of symmetrical co-ordinates should be revised by the British Standards Institution.

Messrs. H. Pearce and **T. T. Evans** (*in reply*): We were interested to hear Dr. Garrard's comments on the invention of the oil-blast circuit breaker by Dr. Ferranti some 30 years ago. It is perhaps unfortunate for the art that this work was not seriously followed, as undoubtedly if the importance of the invention had been realized earlier the progress of oil circuit-breakers would have been more rapid than it has been. On the subject of multi-break switches, we are quite in agreement with Dr. Garrard that it is decidedly a disadvantage to have too many breaks. The only difference between us lies in the fact that we regard two breaks as preferable to four, even for 66-kV and 132-kV breakers, on the very grounds of simplicity which he himself so strongly stresses in another connection. One of the advantages of the cross-jet explosion pot is the self-cleansing action caused by the blast of oil and gas, and as both the arc length and arcing time are reduced, the burning of the contacts is less than with breakers of other construction. Consequently, breakers fitted with cross-jet explosion pots require less maintenance, though we join with Dr Garrard in pressing the importance of regular inspection and proper maintenance of all oil circuit-breakers. The question of butt contacts has always led to divergent views, chiefly because the user would naturally base his opinion upon the result he observes, and his opinion will be good or bad according to whether the design of the butt contacts has been well or ill carried out. We mentioned the fact that the contact resistance is less after a short-circuit than before, not because we wanted to draw attention to the slight difference that can sometimes be measured, but to emphasize the fact that the contact resistance is not impaired by the short-circuit, provided the pressure is maintained. With regard to the rate of rise of recovery voltage, we have drawn attention to the position as we see it at present, and we agree entirely with Dr. Garrard's comments, and anticipate that in the course of time the factor in question will take its proper place in the study of this problem.

Mr. Wedmore gives a very useful survey of the position, and there is little we need say in reply except to make our attitude clear on two points relating to the cross-jet explosion pot. When, by the action of this device, oil is forced towards the arc, the effect is to cool the path of the arc, and the latent heat of vaporization is particularly helpful towards this end. Under the ideal conditions one would wish for a complete path of oil across the gap at the moment of current zero, but this cannot be expected with the present commercial designs. It will be appreciated that we have no wish to minimize the efficacy of this device, and we agree that some tests appear to justify the twofold or threefold improvement suggested by Mr. Wedmore, but until the field has been more widely explored and until we have learnt to utilize, in the fullest manner, the benefits that can be gained, we consider it preferable to limit the assessment of improvement to the figure of 50 per cent over that of the existing plain-break designs.

Mr. Carter draws attention to the desirability of obtaining some recognized standard test-conditions. This is an important piece of work and one which will require very careful study. At first sight it looks a very simple matter to draw up satisfactory conditions, and it is only when the task is actually attempted and discussed with others that it is realized that many difficulties have to be cleared out of the way before there can be any real and useful agreement on this subject. Mr. Carter's attempt to describe our endeavours is not very happy. He suggests that we are attempting to improve switching capacity by using special contacts, whereas we are in fact employing contacts that have been in use for many years. What we have attempted to do is to control the flow of oil resulting from the presence of the arc, in such a manner that the behaviour of the circuit breaker shall be more consistent than that of the plain-break circuit breaker. Our contention is that much testing is required on circuit breakers of all kinds, for we believe that, through lack of data systematically collected and tabulated, the switchgear industry to-day is utilizing far too much space and material in the existing types of oil circuit-breakers. As our knowledge becomes more complete and as modern methods are adopted which lead to more consistent results, considerable improvement is to be expected in this direction. We note with satisfaction Mr. Carter's admission that repeated tests have shown that better performance can be obtained with shrouded contact devices than with plain contacts. With regard to the operation of the cross-jet explosion pot shown in Fig. 4 of the paper, the ejection of the fluid through the path " gc " causes a similar flow through the passage " cc." Mr. Carter does not appear to understand our reference to the inconvenience of the voltage across contacts at the moment of clearing the fault. Provided the current has been finally interrupted, the inconvenience is certainly of very little moment, but unless a rupture occurs at the very first current zero after contact separation the term " inconvenience " is, if anything, a little too mild. In Fig. 6 the inches of arc duration refer to the length of the arc in inches and not to the travel of the breaker, otherwise the curve would have been marked accordingly. In Tables 1 to 3 the 3-phase kVA is calculated from the one recovery voltage recorded. This is permissible because there is practically no variation between the magnitude of the power-frequency component of the recovery voltage on all three phases. The benefits obtained from the cross-jet explosion pot have been dealt with in our reply to Mr. Wedmore. We support Mr. Carter in his statement that tests are required at values definitely above the normal rating of the breaker, but, unfortunately, testing facilities are limited in all directions, and therefore recourse has to be made to separate tests on current and voltage as indicated in the paper. If an engineer cannot get the complete test that he requires, he has to devise expedients by which he may obtain the necessary information in the most effective way.

We are interested in the comparative curves drawn by Mr. Coates, but would explain that we ourselves avoided making comparisons of this kind as it is so difficult to assure that the governing factors are sufficiently similar to make the comparison fair. It is therefore necessary to make this reservation when considering the curves shown by Mr. Coates.

In reply to Dr. Whitney, in Investigation No. 117 the scale of arc power was such that we regarded 20 kW-sec. as the minimum value which could be read on the record. Dr. Whitney also draws attention to the fact that the behaviour of the cross-jet explosion pot on heavy currents is more consistent than on light currents. This is probably due to the reason he indicates, but the range of inconsistency is less than with plain-break circuit breakers and the shroud is so proportioned that in every case rupture takes place while the contact is within the shroud.

The comments of Mr. Rissik are really not quite in order in view of the fact that the paper deals with oil circuit-breakers. We excluded expansion circuit-breakers, gas-blast circuit breakers, and vacuum circuit-breakers from the scope of the paper as we preferred to concentrate on the form of breaker most commonly used in this country, with such variations as modern practice has shown to be desirable. We did this also because we are of the opinion that although something can be learnt from the careful study of any one of these alternative methods, yet for practical service the oil circuit-breaker is likely to hold the field. The desirable properties of oil as an insulator render it one of the best friends the electrical engineer has. Our future efforts should therefore be devoted to extending our knowledge so as to enable oil to be used in the most effective way, rather than to adopt other expedients.

With reference to the communication by Dr. Kopeliowitch and Mr. Brown, we are always willing to subscribe to any test that will reproduce accurately the working conditions, but where this is impracticable we consider it essential for substitute tests to be carried out, and our experience is that the procedure recommended in the paper is a practical solution for the shrouded breakers which we have tested. Even with a shrouded circuit-breaker some variation is to be expected in repeated tests, but fortunately much less than in the case of plain circuit breakers, which Dr. Kopeliowitch and Mr. Brown are apparently prepared to test at reduced rupturing capacity. We have carefully noted the comments made on the calculation of 3-phase kVA, and trust that the various international points of view may be harmonized before long. The statement made with regard to certain single-phase tests would be much more interesting if some further information were given, including, for example, the voltage at which the tests were carried out. In the statement on page 710 we refer to the distribution of static potential in the circuit breaker on any one pole. It is usually tacitly assumed that the potential is uniformly distributed among the breaks in series, whereas this can rarely happen, and this fact must be taken into account in assessing the relative advantages and disadvantages of multiple breaks. The data illustrated in Fig. E furnish still further evidence of the importance of rate of rise of recovery voltage, and it is very clear that this factor will have to be taken into account before the rating of circuit breakers can be considered to be on a satisfactory basis.

DISCUSSION BEFORE THE NORTH-WESTERN CENTRE, 15TH MARCH, 1932, ON THE PAPER BY MESSRS. PEARCE AND EVANS (SEE PAGE 703).

Mr. L. Romero: It is disquieting to reflect that of the hundreds of large and expensive high-rupturing-capacity switches on our system, the great majority will almost certainly never be called upon to break anything like the short-circuit capacity for which they are installed, simply because the necessary faults will not occur. It is even more disquieting to think that later on these switches may have to be replaced by still larger and more expensive switches owing to the growth of short-circuit current values on the system. Switchgear designers will earn the gratitude of users if they can produce an inexpensive device for fitting to existing switches with the object of substantially increasing their breaking capacities.

Mr. S. Ferguson: I am pleased to see that the authors have introduced an important and promising new device. I hope that the paper will convince supply engineers that to design switchgear without tests is mere guesswork, and that a bulky design does not necessarily possess a high rupturing capacity. I do not know why the authors exclude length of break from their list of design features, as it is on this point that many present-day circuit breakers are weak. These switches arc right to the end of the stroke, and then it is a matter of chance whether the circuit is finally interrupted. The pressure either puts out the arc or builds up and destroys the structure. I think that the amount of air cushioning is in many cases only a matter of guesswork on the part of designers. The air volume is fixed so as to provide sufficient air space to avoid oil splashing. The authors' application of Boyle's law should prevent a repetition of the mistake of associating tank pressures and rupturing capacity, without reference to the circuit-breaker design, to which attention has recently been drawn in the Press. The optimum volume of air cushion can be determined only by tests, but my opinion is that most contemporary designs allow too small an air cushion. We recently tried to decrease the air volume employed on our products, with the result that the performance deteriorated and the pressure became excessive. One danger in having an inadequate air cushion is that in his flurry to meet an emergency an operator may close a circuit breaker several times in quick succession in an attempt to burn out the fault; by so doing he develops higher and higher pressures and thus endangers the circuit-breaker structure. I am surprised at the authors' statement that the rectangular circuit-breaker tank was dictated by the necessity for economy in space. I well remember that two leading American switchgear manufacturers introduced their cylindrical-tank circuit-breakers precisely because engineers wanted to install higher-rupturing-capacity circuit-breakers in the space previously occupied by low-rupturing-capacity units. I agree with Mr. Clothier's recent remark* that, as regards the shrouded contact, in the event of failure the final defence must depend on the strength of the enclosure. I am a firm believer in the boiler-type construction of tank and top plate, which a good many manufacturers are now supporting. The worst condition one can have is a small air cushion, which will develop high pressures, and a rectangular tank, which is least able to withstand such pressures. The most important part of the paper is that which deals with the cross-jet explosion-pot, and I congratulate the authors on the work they have done in this direction. I should like to refer to an application of these cross-jet explosion-pots which we undertook in order to increase the rupturing capacity of a circuit breaker without adding to the space occupied. There was no room for the ordinary-type explosion pot, and we could only accommodate a cross-jet pot having half the volume of that used by the authors. When this device was fitted to the circuit breaker the arc duration was reduced from 12 half-cycles to 4 half-cycles, and the maximum arc length from 9·5 in. to 2·5 in. We have not tried varying the speed in order to improve the performance, but the pots successfully interrupted up to 20 000 amperes and up to 44 kV. How should this device be rated? On pages 712 and 720 the authors refer to rating when it is beyond the capacity of the test plant, but they do not state what practice they recommend in this connection. The type of arc control embodied in the cross-jet explosion-pot gives faster operation, prevents synchronous machinery from falling out of step, and provides more consistent performance.

Mr. D. R. Davies: Much research work has been done during the past few years in order to produce a circuit breaker which would give consistent performance with less liberation of arc energy. I have just returned from the United States, where I spent over 3 months directing nearly 500 short-circuit tests on circuit breakers fitted with the cross-jet explosion-pot. Throughout tests made at voltages varying from 4 000 to 110 000 volts the performance of the circuit breaker was exceptionally good; in some cases the only visible signs that it had operated were small wisps of smoke emitted from the vent pipe. A circuit breaker of which the normal rating was 66 kV was successfully tested up to 110 kV. Moreover, although nearly 500 short-circuit tests have been made on two circuit breakers, both of them are in almost as good condition as they were before testing. The arc lengths and arc durations observed during all the tests were much less than any previously obtained with the conventional type of explosion pot, or with plain-break or high-speed contacts. Most of the devices hitherto proposed, and which tests have shown would improve circuit-breaker performance, have certain limitations. In some cases the devices are only suitable for low currents and high voltages: also owing to their size they could not be accommodated in a small circuit-breaker. The cross-jet explosion pot, however, suffers from none of these disadvantages. It has performed as well with high currents at low voltages as with low currents at high voltages. Moreover, it can be accommodated in existing circuit breakers without sacrificing the clearances which are necessary for safety. In circuit breakers intended for 66 kV and upwards, the

* See page 802.

cross-jet explosion-pot reduces the mechanism travel and length of break to approximately 60 per cent of that required with other types of contacts, and it also enables tank volumes to be proportionately reduced. Tests have shown that the duty cycle of the circuit breaker can be considerably increased by fitting the cross-jet explosion-pot. During one series of tests upwards of 24 short-circuits were interrupted without inspection of the contacts, and at the end of the tests the oil and contact deterioration was negligible. During the development stage it was, of course, necessary to consider carefully the various proportions to be adopted. The preliminary tests indicated that the principal dimension which affects arc duration and arc length is the distance from the stationary arcing contact to the first jet. This distance must be long enough to allow the internal pressure to build up to a value which will project oil across the first jet when the moving contact has moved to this position. Moreover, the pressure built up must be sufficient to project the oil across this jet at a velocity of approximately 200 ft. per sec. The velocity required depends on the rate of rise of recovery voltage, and as all the tests were made on a testing plant having a rate of rise of the order of 2 500 volts per micro-second, a velocity of 200 ft. per sec. was necessary. I suggest that Fig. 6 should be supplemented by a curve showing more clearly the relation between arc duration and rate of rise of recovery voltage. High-frequency effects are not recorded by the ordinary magnetic oscillograph: a cathode-ray oscillograph must be used for this purpose. Much work has been done in the United States by Mr. D. C. Prince to establish the relation between the rate of rise of recovery voltage and the velocity of oil which must be projected into the arc to obtain consistent arc rupture during the first two or three half-cycles. Consequently, during the development of the cross-jet explosion-pot it was realized that in order to obtain short arc durations, which are essential if gas liberation is to be reduced to a minimum, a sufficient oil velocity must be obtained in the various jets. After testing seven combinations to determine the rate at which the pressure was built up inside the pot, it was found that if the distance from the arcing contact to the first jet was too short insufficient pressure was developed to give the necessary oil velocity. This distance was then increased until sufficient arc energy was liberated to produce an oil velocity across the first jet of not less than 200 ft. per sec. when the moving contact reached this point. The tests showed that opening speed had an important effect on arc duration. During the first series of tests the no-load speed of the circuit breaker was approximately 7 ft. per sec., and arc durations of 5 to 6 half-cycles were obtained at 66 000 volts: also the arc durations obtained during the make-break-make shots were greater than those obtained with the break shots. On analysing the results it was at once apparent that an increase in opening speed would reduce the arc durations. Consequently, for the next series of tests the no-load speed of the circuit breaker was increased to 9 ft. per sec., when the arc durations were reduced to 3 half-cycles and the arc lengths to approximately 3·5 inches.

Mr. S. R. Mellonie: I should like some more information regarding the operation of the cross-jet device. It is not clear from the illustrations in the paper whether the forces due to the blast of oil operate with or against the magnetic forces on the arc. It seems to me that both possibilities have advantages, as in the one case both forces would operate to accelerate the products of arcing, and in the other the opposing forces would cause a more rapid introduction of cooling oil into the arc. It would be interesting to know whether such devices as the authors describe would double the rupturing capacity of existing oil circuit-breakers.

Mr. A. N. Haworth: The difficulty met with in connection with short-circuit tests is that the observer cannot see what is taking place inside the oil tank, and it is therefore important to examine the circuit-breaker parts after such a test in order to obtain evidence as to the validity of the theories advanced. To give an example, after a short-circuit test on an oil circuit-breaker with butt contacts an examination revealed that the whole surface of each contact was fused and that a greater amount of metal was blown away from the edges remote from the contact lifting rod, these outer edges being rounded off. The inner edges of the contacts, on the other hand, were quite sharp and free from signs of fusing. From this it would appear that as soon as the short-circuit takes place the heavy current heats up the contact joint to welding temperature, so that when the contacts separate they are still joined together by a fused metal bridge of increasing temperature. As soon as the gap between the contacts is great enough the fused metal bridge is forced out into a loop, the ends of which pass over the outer sides of the contacts before the loop is disrupted and the arc proper formed. The metal blown away is chilled by the oil and settles in the bottom of the tank in the form of small globules. The arc length would probably increase at a greater speed than the linear movement of the contact separation, owing to the action of the electromagnetic forces on the arc loop.

Mr. P. G. Ashley: I should like to emphasize the plea made by the authors for closer co-operation between supply engineers and switchgear manufacturers in connection with short-circuit testing of switchgear. Considerable difficulty is met with in computing the efficiency of a range of apparatus when it is only possible to carry out tests on the smaller items in the range. I remember seeing a small mining-type oil circuit-breaker under short-circuit test on a 5 000-kW generator at Carville power station in 1923, when the Electrical Research Association were carrying out some investigations. The circuit breaker had a tank volume of about 1 cub. ft., and with a fairly light tank fitted it successfully ruptured about 75 000 kVA. From results such as this one is tempted to assume better performance figures for the larger circuit breakers. Another important point in this connection is that if supply engineers are afraid to risk tests on their networks, switchgear manufacturers are forced to put down expensive plant for carrying out tests themselves, and the price of circuit breakers so tested must include at least a proportion of the cost of the testing plant.

Mr. G. F. Sills: I should like to refer to the question of the shape of the circuit-breaker tank, mentioned on page 708. The pressures developed in the tanks of oil

circuit-breakers of various rupturing capacities have been determined, and in my opinion the shape of the tank does not matter provided it can withstand the known pressure associated with the rupturing capacity in question. One advantage I have seen put forward for the rectangular tank is that metal phase-partitions separate the three phases, so that, if there is a fault, the fault current flows to earth. Some of the pictures of round-tank circuit-breakers which have been shown indicate that these are of very small diameter, and I cannot imagine that they have metal phase separation right down from the top to the bottom of the tank.

Mr. A. E. Jepson: I should like to ask why the oscillograms reproduced in Fig. 12 show the three phases to be only 60° apart, instead of 120°.

Mr. W. Kidd: To the authors' two essentials to be considered when designing circuit breakers, I should like to add a third, namely that effects must not be produced which will tend to cause breakdown in other parts of the system due to transient conditions. It is a fundamental principle that a flow of energy cannot be stopped instantaneously; there must be a period (though of short duration) and a means of dissipation. The formation of an arc appears to serve this purpose, and, although I agree that the arc must be controlled and ruptured quickly, I should like to have the authors' views as to whether it is possible to produce ill-effects by too quick an extinction of the arc. Until recent years, the Continental oil circuit-breakers offered to us undoubtedly had weak tanks. They all seemed to depend upon the use of a large volume of oil, although Mr. Ferguson's slides and recent research show this view to be quite erroneous.

Mr. O. Howarth: Complaints are made by the authors and by switchgear designers that supply engineers are unwilling to allow the systems and plant for which they are responsible to be used for experimental work on the rupturing performance of circuit breakers. It is not made clear whether a large generator would be sufficient for this purpose or whether the whole of a supply system would be involved. It is my experience that generator designers look with strong disfavour upon any test which subjects a machine to abnormal conditions. It is doubtful whether any machine at present installed in this country would supply more than 250 000 kVA on a short-circuit, and therefore one machine only would be inadequate. Do the authors suggest that at some light-load period a lot of plant should be connected to a system and the switch tested at some point where a considerable fault kVA is obtainable? As the business of supply engineers is to give a continuous and smooth supply to all their consumers, it is not surprising that they will not voluntarily jeopardize this service. Most systems have synchronous plant connected to them, and this may go out of service during a severe disturbance. Supply undertakings cannot maintain the goodwill of their customers if the supply is not maintained; and with the increasing number of uses to which electricity is put by all classes of consumers the importance of freedom from disturbance becomes greater. It must also be borne in mind that the probability of any switch in a generating station having to rupture the full possible fault kVA is very small. Full and frank co-operation between switchgear and supply engineers in the investigation of switchgear failures would provide the designer with much useful information, and as the failures are usually spread over a number of different undertakings the frequency of disturbance on each would be so low as to have little detrimental effect upon its relations with its consumers.

Mr. R. Brooks: Well-equipped companies who are prepared to spend money upon investigations are dealing with the problem of oil circuit-breaker design by logically-planned schemes of research, and these investigations are being pursued with an energy which augurs well for the future of this class of apparatus.

Mr. G. H. Sammons: The large number of changes which are being made in switchgear design render it advisable to replace switchgear every year, on the lines followed by the motor-car industry. The supply engineer makes his choice from square, round, single, or triple tanks; brush, plain, solenoid, knife, shrouded, or ball contacts; with oil, water, or air breaks—only to learn as soon as the gear is installed that something new is necessary. To replace switchgear at short intervals would not, however, be possible from the economic point of view. Assuming that the shrouded contact shows increased efficiency, its most useful field is in its adaptation to already-installed switchgear, a feature wherein it appears to be unique. Referring to Figs. 2 and 4, in Fig. 2 the fixed contacts appear to be adjustable, being mounted on springs, whereas in Fig. 4 the fixed contact appears to be a solid tube, in which case there is no adjustment. If through any mischance the contact were burnt the charring would reduce its diameter, and it would not make good contact in the solid tube the next time it was inserted. With regard to the testing of switchgear on supply systems, there is a reason for the lack of enthusiasm shown by operators. In the first place, what do the designers require? Secondly, what is the technical desideratum? To test each switch *in situ* is, I suppose, an answer to both questions. It must be remembered, however, that a supply system usually consists of old as well as new cables, switches, machines, and consumers' apparatus, and every shock imposed on the system serves to weaken all apparatus connected thereto. One certain result of such a practice would be to provide more opportunities for switchgear to operate.

Mr. C. S. S. Baldwin (*communicated*): A certain amount of guesswork enters into all designing, but it can only be justified when based on wide practical knowledge. It would seem, therefore, that the suggested co-operation of supply authority and manufacturer could best be effected, with minimum cost to both parties, by the supply authorities giving a regular periodical supply of field data and the manufacturers determining their own experimental data. Again, in view of the fact that when the national "grid" is fully in commission many stations at present equipped with generating plant will become obsolete, I suggest that manufacturers should get in touch with the Central Electricity Board with a view to making use of the disused machines for oil circuit-breaker testing at week-ends. Whilst this idea may not appeal to the larger manufacturers who have access to the test results of the big American concerns with which they are associated,

it would assist smaller manufacturers in this country to develop their apparatus so that they might compete favourably in the market. Although reference has been made in the discussion to Continental oil circuit-breakers, none of the speakers have mentioned the tendency to use vapour for the purpose of extinguishing the arc. This idea is receiving great attention in Germany. Is there not a possibility that the vapour arc-extinguishing type of circuit breaker may oust the orthodox oil circuit-breaker? If so, owing to our concentrating too closely on the development of the present recognized method, we in this country are soon likely to find our designs out of date. The vapour-type circuit-breaker minimizes the risk of fire and explosion, and is, I believe, very efficient. In Fig. 4 the authors show a cross-jet type of contact in which a plug-and-socket scheme is adopted. I assume that the sketch is only diagrammatic, and that in actual fact some provision is made for self-alignment so as to ensure an even contact surface.

Messrs. H. Pearce and **T. T. Evans** (*in reply*): Mr. Romero draws attention to two features of the circuit-breaker situation which taken separately are more disquieting than when considered together, since they have a neutralizing action one upon the other. While the design of the cross-jet explosion pot was considered primarily from the standpoint of its use in new breakers, the fact that the design is comparatively simple and compact makes it very suitable for fitting to existing circuit breakers.

Mr. Ferguson suggests that the length of break should have been included in this paper as one of the design features of a circuit breaker. In this connection we would say that in our opinion it is desirable for the length of break to be so selected that the arc is ruptured before the breaker reaches the end of its stroke. Even this, however, has no universal application, since, for example, in a breaker of the impulse type the whole feature of the design is to use a very short break and to increase the insulation value of the arc path between the contacts by a flow of oil at high velocity, and thus ensure the rupture of the arc. This suggests that it would be effective provided, and only provided, that adequate steps are taken to ensure this increase in the insulation of the arc path; otherwise it is safer to adopt the more conservative rule mentioned above. In practice the length of the arc varies appreciably in different designs of circuit breakers, and so long as the circuit characteristics are the same the length of break required may be regarded as a measure of the failure to raise the insulation value quickly enough. Where the movement of the oil is controlled, the length of arc under similar conditions is found to be much more consistent than in plain-break circuit breakers, where the vagaries of oil movement have the greatest play. With regard to the air cushion, we note that Mr. Ferguson agrees with us that this is a subject on which designers have had a wide divergence of opinion. The precise result of varying the air cushion can only be satisfactorily observed by experiment, though once the cushion is reduced below a certain volume it is safe to predict that any further reduction will increase the stresses on the circuit-breaker tank and top plate, so that where this is already the limiting factor the maximum short-circuit capacity of the circuit breaker is thereby reduced, quite apart from whatever effect the change has on the movement of oil.

Several speakers in the discussions at London and Manchester dealt with the subject of circular versus rectangular tanks. The position so far as the user is concerned is: Will the tank do its job? What space will it occupy, and how is the cost affected? The first question is answered by test-results and test-results only. The answer to the second question, in spite of Mr. Ferguson's comment, is definitely in favour of rectangular tanks, since the manufacturers to whom he refers achieved an increase in the rupturing capacity not by the change to round tanks but by other and more important changes in design. The answer to the third question depends upon the arrangement of the equipment as a whole, and on the manufacturers' standards; in practice there is usually little difference in the final result. We are much interested to hear of Mr. Ferguson's application of the cross-jet explosion pot to one of his existing breakers, but without considerably more information than he gives we should hesitate to advise him as to the rating. Our general attitude with regard to the rating of breakers where full-power tests cannot be employed is that it is the duty of the designer to secure as much evidence as he can that the breaker will meet separately the various limiting conditions. One does not hesitate to calibrate a watt-hour meter with separate current and voltage supplies, because one knows that each factor is independent of the other. The more confident a designer is of such independence the more he is justified in adopting procedure of this kind. In the light of the evidence that we at present have, we should expect to be able to regard tests on the cross-jet explosion pot in the same manner, but as we have learnt that it is desirable to proceed steadily step by step we prefer to limit at present our assessment of the improvement due to the cross-jet explosion pot to approximately 50 per cent, thus obtaining a larger factor of safety as well as reserving a margin to cover contingencies that may arise in operation.

Mr. Davies's comments are particularly interesting as they refer to a further series of tests on the cross-jet explosion pot which have been carried out since our paper was written. Until oil circuit-breaker design can be dealt with quantitatively in the manner of machine design, our knowledge must be obtained experimentally, and for this reason we carried out tests on a number of different combinations before finally choosing the best combination. We should like to sound a note of warning as to the significance of the velocity of 200 ft. per sec. mentioned by Mr. Davies. When a fluid moves along a pipe it has a translational velocity of a fairly definite amount, which can be measured and recorded, but in circuit breakers where the whole disturbance is over in less than 0·1 sec., and in a confined space such as an explosion pot, where there is violent turbulence, the interpretation of velocity requires very careful measurement and study before it can be regarded as comparable with ordinary measurement.

In reply to Mr. Mellonie, the usual arrangement of a cross-jet explosion pot is such that the magnetic force on the arc and the blast of oil are both in the same direction, though the former has little opportunity of extending the arc appreciably owing to the confining

effect of the shroud. The addition of the cross-jet explosion pot to existing breakers would undoubtedly increase the rupturing capacity of those breakers, and in some cases the figure might be doubled, but each case would have to be considered on its merits, and our general tendency is to assume a lower figure of 50 per cent and thus ensure a higher safety factor than before.

Mr. Haworth draws attention to the importance of careful examination in detail after tests, in order to obtain all the information the results can give. It is a general truth that the greater the experience of the experimenter the more is learnt from the experiment.

Mr. Ashley wisely stresses the importance of a number of tests before assuming that a rating has been justified. This applies particularly to plain-break circuit breakers, as was demonstrated by Mr. Wedmore some years ago.

We agree with Mr. Sills's comments on the shape of the circuit-breaker tank.

Mr. Jepson points out that the 3-phase currents in the oscillogram of Fig. 12 have not the regular displacement of 120°. This is due to the polarity of one of the phases being reversed.

Mr. Kidd raises the question whether the arc can be ruptured too quickly. As he surmises, the results are disastrous when this occurs, but so long as he uses oil circuit-breakers he has no need to fear this since the oil circuit-breaker has the virtue of always breaking current at the zero point of the wave, which means that the flow of energy is interrupted at a moment when it is in equilibrium. In order to achieve a rupture more quickly than this, some sort of a vacuum would be required, and any vacuum circuit-breaker requires to be proved immune from this objection. The simplest mechanical analogy is the stopping of a pendulum at various parts of the stroke.

Mr. Howarth suggests that generator designers look with strong disfavour upon any test which subjects a machine to abnormal conditions. We cannot quite understand this assertion in view of the fact, stated in the paper, that it is the practice of the company with which we are associated to carry out short-circuit tests on every new turbo machine manufactured. Mr. Howarth's estimate of 250 000 kVA as the maximum short-circuit power obtainable from any one machine installed in this country is rather too low. If he will refer to Test No. 20, Table 3, he will see that we have recorded a test of over 200 000 kVA on a single machine with a transformer in circuit. Without the additional reactance of the transformer the short-circuit current on the generating voltage would be appreciably higher. We do very seriously suggest that a number of machines should be connected to a system during the light-load period in order to obtain short-circuits of considerable capacity, but we do not suggest that such an arrangement is likely to jeopardize the service. On the other hand we maintain that it is desirable for any slight weaknesses that may be displayed in the complete equipment during such tests to be brought to light in order to ensure that such weaknesses will not jeopardize the system at some time when the conditions of operation are beyond the immediate control of the operators. Mr. Howarth rightly points out the desirability of full and frank co-operation between switchgear and supply engineers, and it is perhaps a testimonial to British switchgear manufacturers that the troubles experienced in the past have not been sufficiently serious to encourage the supply undertakings to insist upon tests on oil circuit-breakers such as they have upon almost every other part of their equipment.

Mr. Sammons makes a very interesting comparison between the switchgear and motor-car industries, and it will be readily admitted that the latter has advanced faster than most branches of industry during the last few years. One of the most effective reasons for this is that by the very nature of the article every motor-car is fully tested and proved under every conceivable kind of working condition. In this respect it is widely different from the circuit breaker, which is only proved at long intervals, and then usually at times and under conditions when very little evidence is gathered to guide designer or user as to the essential features required to effect improvement in future service. The adjustment of the fixed contact is not indicated in Fig. 4, where only those features are shown which indicate the difference between this kind of circuit breaker and those of normal construction. A resilient contact is, of course, essential to any kind of circuit breaker. With regard to tests on site, these would naturally not involve the whole of the system, but only such machines, switchgear, and interconnectors, as are actually required in order to carry out the tests, and there would therefore be no great difficulty in avoiding the risk of unduly stressing equipment which might have become too old for its duty. If any such portion of a system is liable to break down on the occurrence of a short-circuit test, it is high time that the supply undertaking was aware of the condition and took steps to remove it.

Mr. Baldwin makes the interesting proposal that obsolete plant could be utilized for testing on site, and this is undoubtedly a matter which might be considered by the Central Electricity Board and other authorities. After all, it is the users that gain most by the proving of equipment, and it is to them that the industry should look for support of this view. Other points raised by Mr. Baldwin are dealt with in our reply to Mr. Sammons and in our reply to the London discussion (see page 730).

THE CHANGE-OVER OF LOW-TENSION DISTRIBUTION SYSTEMS FROM DIRECT CURRENT TO ALTERNATING CURRENT.

By H. BLADES and A. C. MACQUEEN, Associate Members.

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SUMMARY.

The object of the paper is to indicate that the changing-over of existing low-tension networks from direct current to alternating current can be carried out in a satisfactory and advantageous manner from an engineering as well as from an economic standpoint.

The problems arising in dealing with small townships, and with suburban and residential areas, are quite different from those which arise in industrial and city areas. The paper has consequently been divided into three parts, Part 1 dealing with suburban and residential areas, Part 2 with industrial and city areas, and Part 3 with the general aspect of changing over.

As a result of investigations, the authors are of the opinion that, irrespective of loading conditions, residential and suburban areas should be changed over to a.c. supply at the earliest possible opportunity, but that in industrial and city areas the rate of change-over should depend upon the growth of the d.c. load and the condition of the d.c. converting plant. In all areas, however, the "standard" 3-phase 4-wire a.c. system should ultimately be adopted.

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INTRODUCTION.

The advantages to be derived by users of electricity and manufacturers of electrical apparatus from standardization in the voltage and type of current supplied are well known. The Central Electricity Board is at present engaged in the standardization of frequency, but this work only affects a proportion of the users of electricity, principally those receiving high-tension supply. Table 1 gives an approximate idea of the number and types of low-tension supply systems which are operating in Great Britain. Undoubtedly a state of great confusion exists, and the question of standardization of low-tension systems is of the utmost importance.

TABLE 1.

Approximate Analysis of Systems of Supply in Great Britain as obtained from the Engineering and Financial Statistics published by the Electricity Commisssion, relating to Electricity Supply for the Year ending March, 1930.

(*a*) Supply authorities giving	D* only	149
	D and A_1†	11
	D and A_2‡	2
	D and A_3§	161
	D, A_1, and A_2	0
	D, A_1, and A_3	52
	D, A_1, A_2, and A_3	3
	D, A_2, and A_3	6
	A_1 only	21
	A_2 only	4
	A_3 only	180
	A_1 and A_2	2
	A_2 and A_3	8
	A_1 and A_3	29
	A_1, A_2, and A_3	5
(*b*) Number of	d.c. systems	244
	single-phase systems	123
	two-phase systems	30
	three-phase systems	444

Although where new systems are being laid down a standard 3-phase 4-wire system at a pressure of 400/230 volts is being adopted, as indicated in Table 1 there are still numerous non-standard systems, the majority operating on direct current. Users of these non-standard types of supply and manufacturers of apparatus connected thereto will, no doubt, wish to participate in the benefits of standardization, and in the near future a strong demand may be expected for a national standard of low-tension supply.

The Central Electricity Board is at present engaged, at a heavy expenditure, in securing the maximum efficiency in the generation and transmission of electrical energy, but it is equally important to obtain increased efficiency in its distribution. The recent high rate of increase in the demand for electricity, and the belief

* Direct current. † Single-phase. ‡ Two-phase. § Three phase.

that the future will bring a still more rapid growth of load, have compelled supply authorities to consider increasing the capacity of their low-tension distribution systems; and the authors have endeavoured to show that where the present supply is by direct current this increase in capacity may be obtained concurrently with the advantages of standardization and increased efficiency at a reasonable expenditure by means of a change-over to alternating current.

PART I. CHANGE-OVER IN SMALL TOWNSHIPS AND RESIDENTIAL AND SUBURBAN AREAS OF A LARGE CITY.

Short Comparison of D.C. and A.C. Systems.

The relative advantages of d.c. and a.c. distribution have been discussed on numerous occasions and it is not proposed to enter into details of the merits of the different systems, but a brief summary is necessary, as the comparison has a distinct bearing on the subject of this paper.

For the purpose of this comparison the standard 50-cycle 3-phase 4-wire a.c. 400/230-volt system will be compared with the 3-wire 460/230-volt d.c. system.

The advantages of the a.c. system compared with the d.c. system are:—

(1) Reduction in capital outlay, due to smaller and cheaper substations and substation equipment and cheaper low-tension networks.

(2) Reduction in maintenance costs on transformer substations and plant compared with rectifier or convertor substations and plant; and on the low-tension networks, due to freedom from electrolysis and osmotic action, and consequent large reduction in the number of faults.

(3) Reduction in valuation for rating purposes.

(4) Increased efficiency, due to reduction in running losses of transformers as compared with transformers plus convertors or rectifiers, and due also to the smaller feeding radius of substations.

(5) Increase in elasticity of system due to: (*a*) increase in number of substations, (*b*) comparative ease with which increase of load or alteration of load centre may be met by inserting a transformer centre where required, and (*c*) greater ease with which a heavy low-tension a.c. consumer may be transferred to high-tension supply.

In the areas covered by Part 1 most of the load would be approximately non-inductive. The power factor would therefore be good and the effect of wattless kVA on the system slight. Apart from this, from the point of view of a supply undertaking it may be said that an a.c. system has practically no disadvantage when compared with a d.c. system.

Reasons for Change-over.

There seems no doubt, therefore, that an a.c. system of distribution is better than a d.c. system, but, where the latter is already in existence, supply engineers have to decide whether it is worth while to alter it in order to obtain the advantages enumerated above.

Apart from the inherent advantages of the a.c. system, the demand for standardization and the abnormal growth of load within the last few years have compelled consideration of the question of change-over.

As already stated, the demand for a standard system of low-tension supply is yearly becoming more insistent. At present consumers cannot with confidence buy any considerable amount of electrical apparatus, because if they move to a different part of the country or even a different part of the same town the type of supply may be different and their apparatus useless. Manufacturers cannot supply or quote for the supply of electrical apparatus without lengthy inquiries as to the type of supply available. Further, a standard system should reduce the cost of electrical apparatus and thereby probably increase the demand for electricity.

The recent rapid growth in the demand for electricity has resulted in many existing d.c. systems becoming overloaded, and to make proper provision for the future it would in some cases be necessary to double or even quadruple their carrying capacity at a heavy expenditure in d.c. plant and cables. If without an undue increase in this expenditure the necessary areas could be changed to alternating current and at the same time the increased capacity obtained, there would be no doubt as to the advantage of this course.

There are various ways of obtaining the increased capacity desired. It will be shown later that it is less expensive to install an a.c. centre and change over the network to be supplied from it than to erect a d.c. substation of equivalent capacity, provided the maximum demand on the network is less than 60 per cent of the plant capacity of the centre.

It will also be shown that where the maximum demand of a d.c. centre equals 75 per cent of its plant capacity, the cost of doubling the capacity of the centre by installing a.c. plant and changing over the network, is little more than the cost of doubling the capacity by extending the building and installing additional d.c. plant and mains.

The capacity of a system can also be increased by erecting an a.c. centre and changing over part of the network instead of adding to an existing d.c. substation. The comparative costs depend upon the distance of the nearest high-tension cable from the site of the new centre, and upon the expenditure necessary for low-tension cables. Usually, it will be found much cheaper to install the a.c. centre and to change over.

Small townships at present generating direct current for their own use have an additional inducement to change their supply to alternating current. In all likelihood their plant will be shut down in the near future, and they will receive supply from the national "grid." If d.c. distribution were to be continued the cost of the necessary transformers and converting plant would be borne by the Central Electricity Board, but if it were decided to change the supply to alternating current nearly the whole of the estimated costs of transformers and convertors necessary for continuing d.c. supply might still be obtained from the Board and used towards the cost of changing over.

Assuming that the maximum demand equals 75 per cent of their plant capacity and that to provide for future development the undertakers decided to double

the capacity of their system, an approximate comparison of costs is given in Table 2.

TABLE 2.

	Continuing d.c. supply	Changing-over to 3-phase system	Changing-over to single-phase system
	£ per kW	£ per kW	£ per kW
Cost of replacing existing capacity	8·0	1·5	1·7
Cost of additional capacity, including additional switchgear, mains, etc.	13·5	5·0	5·3
Total cost of changing-over	—	12·5	9·5
Estimate of cost chargeable to or recoverable from Central Board ..	8·0	6·5	6·5
Total cost to undertakers	13·5	12·5	10·0

CHOICE OF SYSTEM.

For obvious reasons the only a.c. systems considered are the 3-phase 4-wire system with pressures of 400 volts between phases and 230 volts from phase to neutral, and the single-phase 3-wire system with 460 volts between outers and 230 volts from phase to neutral. The former will be referred to hereafter as the "standard" system, and the latter as the single-phase system.

The "standard" system is undoubtedly the better one, and its advantages have been fully discussed in a previous paper by Messrs. Beard and Haldane.* Unfortunately, owing to the presence of a large proportion of 3-wire mains in the majority of d.c. systems, financial considerations compel consideration of single-phase distribution.

From an engineering point of view the single-phase system has certain disadvantages (which will be dealt with later) when compared with the standard system, but the great advantage in its use is that existing 3-core cables can be fully utilized and the only new mains required in changing an area over are those necessary for development. The problem, therefore, becomes a dual one of engineering and finance, and it may be necessary to compromise by changing from d.c. supply to single-phase distribution with a view to a "standard" a.c. system at a later date.

In the opinion of the authors, therefore, in changing from d.c. supply to a.c. distribution there are three alternatives, viz.:—

(1) Change-over to a "standard" a.c. system of supply.
(2) Change-over to a single-phase system of supply.
(3) Change-over to a temporary single-phase system of supply.

* *Journal I.E.E.*, 1927, vol. 65, p. 97.

(1) *Change-over from D.C. Supply to a "Standard" A.C. System.*

The chief difficulty in changing from a d.c. 3-wire supply to a "standard" system is the presence of 3-wire cables and network boxes in the d.c. network. A large proportion of the latter have to be replaced by, or converted to, 4-wire boxes, but owing to the excessive cost

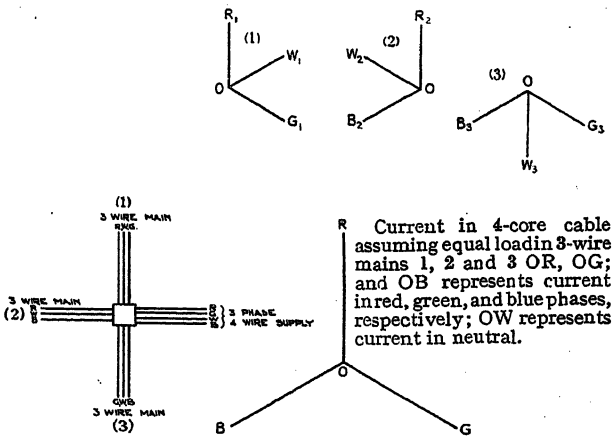
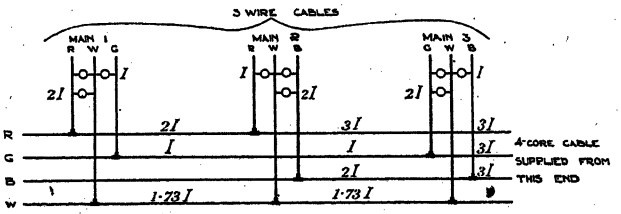


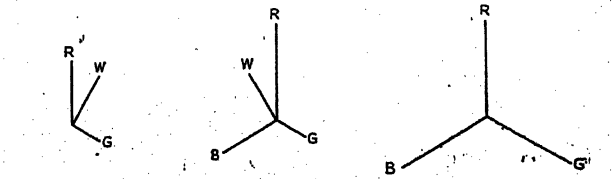
FIG. 1.—Showing (on left) the use of 3-wire mains on "standard" a.c. supply, and (on right) current vectors drawn to a comparative scale, assuming balanced conditions.

of replacements the existing 3-wire mains have to be utilized as far as possible.

From an a.c. centre, 3-phase 4-wire supply has to be taken to suitable "balancing" points in the network, either by laying down new 4-core feeders or by using



(*a*) Diagram showing conditions due to unbalanced loading in 3-wire mains connected to 3-phase supply assuming currents in G_1, R_2, and $B_3 = I$, and currents in R_1, B_2, and $G_3 = 2I$



Current in 4-core cable between mains 1 and 2. Current in 4-core cable between mains 2 and 3. Current in 4-core cable on supply side of main 3.

(*b*) Vectors drawn to a comparative scale showing currents in 4-core main corresponding to conditions in (*a*)

FIG. 2.—Alternative method of use of 3-wire mains for "standard" a.c. supply.

two or more existing 3-wire cables to form one 4-wire feeder. From these "balancing points" the 3-wire distributors can be supplied on two phases and neutral as shown in Figs. 1 and 2.

Assuming unity power factor throughout, the current vectors for supply to 3-wire mains from two phases 120° apart are shown in Figs. 1 and 2. Where the phase currents are equal the current in the neutral is equal to that in each of the phases, and where the phase currents are unbalanced the neutral current is equal to the square root of the sum of the squares of the phase currents minus their product or, referring to Fig. 1, OW = OR = OG for balanced conditions, and $OW = \sqrt{[(OG)^2 + (OR)^2 - (OG)(OR)]}$ for unbalanced conditions.

If each 3-wire main has to be considered separately, the methods shown in Figs. 1 and 2 are obviously inefficient methods of supply, but when an area is considered as a whole there are other factors which in some cases more than compensate for the loss due to the currents in the neutral. Fortunately, in many supply undertakings a good proportion of the total mains in suburban areas are 4-core, in anticipation of a change-over. On a single-phase supply one core of these 4-core cables would be idle. On the "standard" system the reduction in losses due to using all the cores of the 4-core cables is greater than the loss due to the current in the neutrals of the 3-wire mains, provided the proportion of 4-core cables is sufficiently great.

If the neutral conductor is of the same cross-section as the phase conductors, and assuming equal voltage and loading, to deliver the same power the I^2R loss on a 3-wire distributor is 50 per cent greater on a 3-phase supply than on a single-phase supply. Under the same conditions a 4-core distributor on a single-phase supply with one "idle" core would have a 50 per cent greater I^2R loss on a single-phase supply than on a 3-phase supply, using all cores.

With uniform loading, therefore, considering distributors only, it is more efficient to supply an area on the "standard" system than on single-phase if more than 50 per cent of the distributors are 4-core. A perfect balance is rarely obtained on any distributor, and in practice the above figure would probably be reduced to less than 45 per cent.

On a "standard" a.c. system all feeders would be 4-core, and these are the most heavily loaded cables in a network.

The proportion of 4-core mains which turns the balance in favour of a "standard" a.c. supply varies with local conditions, and each case must be considered on its merits. The results of an actual investigation are given below. A developing area was supplied from two d.c. substations about 1½ miles apart. It was decided to change this area over to alternating current and to insert a transforming centre approximately midway between these substations. Short lengths of new mains were necessary to provide an outlet from the transforming centre to the network.

The total lengths of mains to be supplied from this centre were:—

3-wire mains	5 100 yards
4-core mains (including new feeders) ..	2 700 yards
Percentage of 4-core mains in the area..	34·6 per cent

The efficiency was calculated for "standard" a.c. supply and for single-phase, and the losses were found to be 19 per cent greater on the single-phase than on the 3-phase system. It was found possible in this case so to re-design the network that to a great extent the 3-wire mains only carried their own individual load, while the 4-core mains carried the sum of the currents in the 3-wire mains. The load was increasing rapidly, and as new 4-core mains were laid to meet the increased demand the advantage in efficiency of the standard system as compared with the single-phase system would become greater.

Under favourable conditions, if reasonable care is exercised when a d.c. network is being re-designed for a.c. supply it may be more efficient to adopt the "standard" system than single-phase supply, even if the proportion of 4-core mains is less than 30 per cent of the total mains.

When a 3-wire main is supplied by two phases and neutral from a "standard" a.c. system there is a certain voltage-drop due to the current in the neutral. The voltage-drop between a phase conductor and a neutral conductor of a 3-wire main is equal to the vector sum of the e.m.f.'s necessary to overcome the impedance of these conductors, and on a non-reactive circuit these e.m.f.'s are proportional to the resistances and in phase with the currents.

In practice when an area containing 3-wire mains has been changed over to "standard" a.c. supply, little trouble will be experienced due to voltage regulation because:—

(*a*) Owing to the smaller cost of an a.c. distribution centre compared with that of a d.c. centre, the feeding radius of the former will usually be much less than that of the latter.

(*b*) On d.c. supply one core of the 4-core mains in the area would be "idle."

Assuming equal voltage and unity power factor, to deliver the same power, the current per conductor and therefore the voltage-drop on these 4-core mains would be 33·3 per cent less on a.c. supply than on d.c. supply, because of using the fourth core. The reduction in voltage-drop on the 4-core cables would tend to minimize the effect of the increase of voltage-drop on the 3-wire mains.

(*c*) As mentioned with regard to I^2R losses, the current in the neutral of the 3-wire mains can be reduced by exercising reasonable care when an area is being re-designed for a.c. supply.

It is suggested, therefore, that the following areas should be changed from direct current to the "standard" system:—

(1) Where the proportion of 4-core cables plus the necessary new cables is about 30 per cent of the total mains.

(2) Where the development is likely to be such that within a reasonable time the new cables necessary will be sufficient to make the proportion of 4-core mains 30 per cent of the total.

When an examination of a supply area shows that it is a practical proposition to change the majority of distributing centres to "standard" a.c. supply it is advisable to adopt, as far as possible, this system for the whole area.

Referring to Fig. 3, the network from substations A, B, C, and D, may be suitable for the standard system, but on that supplied from E the proportion of 4-core cables may be very small and a large increase in load may not be expected.

In such a case, although it is less efficient to supply

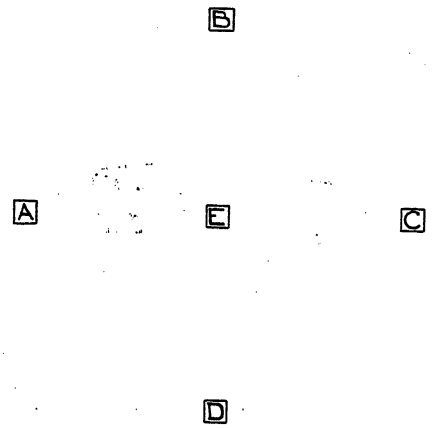


FIG. 3.—A, B, C, D, and E, represent low-tension distribution centres.

the network from E on the "standard" system, it is obviously undesirable to insert a single-phase system in the midst of a 3-phase distribution, and it may be possible by a small outlay on new mains to adopt the

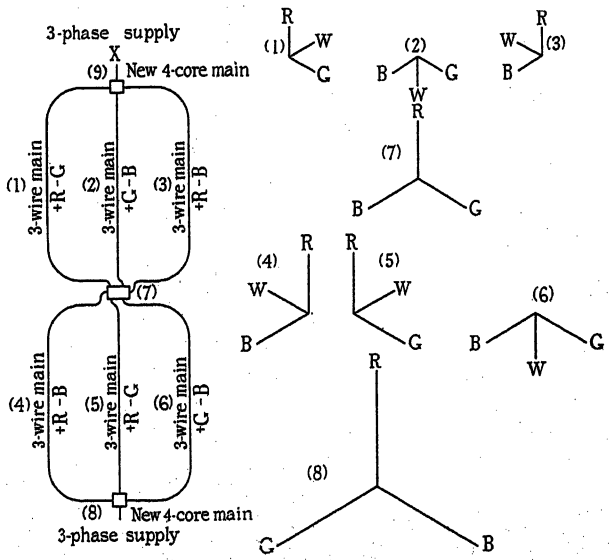


FIG. 4.—Showing (on left) the utilization of 3-wire mains on "standard" a.c. supply, and (on right) current vectors drawn to a comparative scale, assuming, in sections (1) to (6) inclusive, (*a*) equal loading per section, (*b*) the load concentrated at the centre of each section, and (*c*) each section to be of the same length and resistance.

standard system. An example of this is given in Fig. 4. The signs (+) and (−) refer to the d.c. system and the letters R, G, and B, represent the phases of the a.c. system. Thus on section (1) the d.c. positive conductor becomes the red phase and the negative conductor becomes the green phase, and so on. The d.c. neutral remains the a.c. neutral throughout, and in the vector diagrams the a.c. neutral currents are indicated by the vectors marked W.

Fig. 4 shows the extreme case of a housing estate where all the mains are 3-wire with the exception of the short road-crossing sections (8) and (9), which would be replaced with 4-core cables, the former to give supply to the estate and the latter to provide a stand-by from the point X. Section (9) also provides a 3-phase 4-wire stand-by to X from the estate. Sections (4), (5), and (6), may be regarded as a 3-phase main with two cores per phase. An examination of the vectors in Fig. 4 shows that, provided a reasonable balance can be obtained, the losses are not excessive. Assuming balanced conditions and uniform loading, and provided the neutral conductor is of the same cross-section as the phase conductors, the I^2R loss on the 3-wire mains would only be approximately 26 per cent less on the single-phase than on the "standard" system.

Fig. 5 shows a method of giving "standard" a.c.

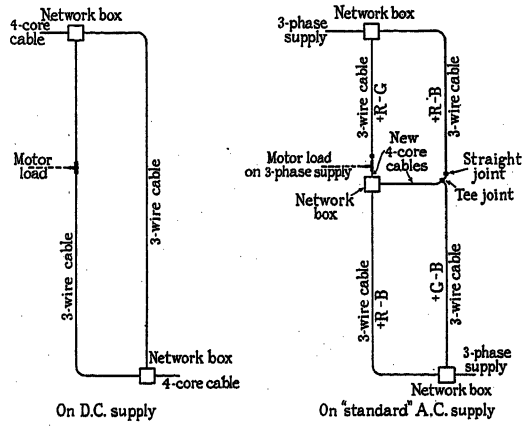


FIG. 5.

supply to a road which has a 3-wire main laid on either side. For various reasons it may be undesirable to replace these mains even although a consumer with a heavy motor load may be situated near the centre of the road. By installing a network box, laying a short length of 4-core cable across the road, and replacing that length of 3-wire main between the network box and the power consumer with 4-core main, a 3-phase 4-wire supply can be given to deal with the motor load, with a resultant reduction in the neutral currents in the 3-wire mains and an improvement in the voltage regulation.

Utilization of Existing 3-core Feeders.—As already stated, only 4-core feeders can be used on a standard a.c. system, but to some extent existing 3-wire feeders can be utilized by bunching two or more together to form one 3-phase feeder, by using static balancers at feeding points, or by running an additional single-core cable to form the fourth wire. To a limited extent 3-core feeders can be used as phase boosters, the neutral return being obtained through another feeder.

Design.—There are a few points which may materially increase efficiency when re-designing a d.c. network for "standard" a.c. supply, viz.:—

(*a*) To re-design the network so that, as far as possible, the 3-core mains only carry their own individual load, while the 4-core mains carry the sum of the loads on the 3-wire cables.

(*b*) To interlink or join the neutrals of the 3-wire cables as much as possible and so reduce the current in the neutral.

(*c*) To make any one length of a 3-wire main on the same two phases as short as possible and so reduce the current in the neutral.

(*d*) To have an accurate record of consumers' loads to enable a correct balance to be carried out.

Colours.—It is essential that the cable-core colours already in use on d.c. supply be retained when the system is changed over to alternating current. Thus, if on direct current the positive conductor is coloured red, the negative blue, and the neutral white, when the system is changed to alternating current the respective phase conductors would be red, green, and blue, and the neutral white. On a network with the above core colours, when the 3-wire mains are being balanced for standard a.c. supply the d.c. positive conductor should only be transferred to the red and green phases and the old negative conductor to the green and blue phases, so that on the 3-wire cables the red phase is always represented by a red core, the blue phase by a blue core, and the green phase by both red and blue cores. This method, which is illustrated in Figs. 1, 2, 4, and 5, is a distinct advantage as regards service connection, jointing, and fault location.

(2) *Change-over from D.C. Supply to Single-Phase Supply.*

It is impossible to give an efficient "standard" system of supply to areas in which the proportion of 4-core mains is very small and which, from the point of view of present requirements, are well developed electrically, unless heavy expenditure is undertaken for replacements. The single-phase system has therefore to be considered.

On single-phase supply full use can be made of existing suitable 3-wire cables, but unfortunately this system has certain disadvantages when compared with the "standard" system.

There are a number of different methods of obtaining low-tension single-phase 3-wire supply from a 3-phase high-tension system. Space does not permit of a detailed description of each of these methods, but four of the best known are indicated in Fig. 6.

A short comparison of these methods of transformation is given in Table 3.

In addition to the disadvantages stated above, there are others which are common to all single-phase systems, viz.:—

Difficulty in Supply of Motor Load.—Even in suburban areas there are a number of motors, and the known difficulties of starting current, starting torque, etc., of the single-phase motor may seriously affect the voltage regulation of the network and cause dissatisfaction to consumers who have been accustomed to d.c. motors. Although recently there has been a great improvement in the design of single-phase motors, they still cannot compete in cost and operation with 3-phase motors except for very small outputs.

Non-standard Voltage.—While the voltage between phases and neutral would be "standard," that between outers would be non-standard.

Not one of the methods described in Table 3 is ideal. The majority of supply authorities giving a single-phase supply have adopted either the Scott or the delta/double-star method. In the opinion of the authors the latter is the better system, principally because a "standard" 3-phase supply can be obtained from the same source at the same time as a single-phase supply, and because standard transformers and switchgear can be used on single-phase and adapted for 3-phase supply at a later date. Re-designing a d.c. network for a single-phase system supplied from a delta/double-star transformer presents certain difficulties because the network from each centre has to be divided into three

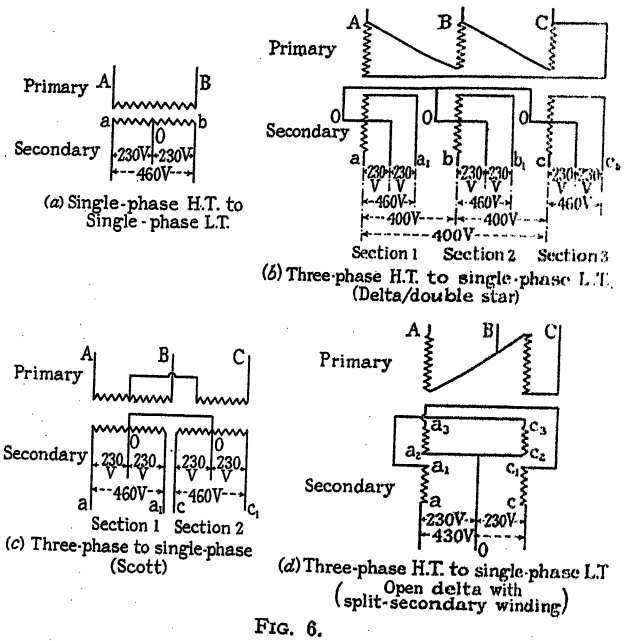


FIG. 6.

distinct sections, as shown in Fig. 6(*b*). Each section should carry approximately the same load, and to provide interlinking and stand-by facilities the sections fed from one centre must as far as possible meet the corresponding sections from adjoining centres.

It will be seen, therefore, that any single-phase system compares unfavourably with the "standard" system, and as a permanent means of distribution is rather difficult to justify. If, however, a temporary single-phase supply could be adopted as a step towards a permanent "standard" system there would be ample justification for it.

(3) *Change-over from D.C. Supply to a Temporary Single-Phase System.*

The chief objection to a temporary single-phase supply is that a second change-over is necessary, and the questions which arise are:—

(*a*) When is the second change-over to take place?
(*b*) What will be the cost of the second change-over?
(*c*) What inconvenience will be caused to consumers by the second change-over?

(*a*) Although an area may be electrically well developed at present, the future will undoubtedly bring an increase of load. New mains will therefore be required for reinforcing existing mains, supplying new consumers, and for providing an outlet to the network from new transforming centres. If all these new cables are 4-core it should not be long before the different areas could be operated more efficiently on the "standard" system than on single-phase.

(*b*) In suburban areas there are usually few heavy power consumers, and they are often grouped near the load centre of a supply area and hence near the transforming centre. If delta/double-star transformation is used, it may be possible to change the area including the power consumers from direct current to the "standard" system while the purely residential part of the area is changed to single-phase. Apart from that used by power consumers, any apparatus would be connected between phase and neutral and would not require changing. The cost, therefore, of changing consumers' apparatus from the single-phase to the "standard" system of supply would be very small.

The expenditure on mains would also be small because, as new 4-core cables were laid while the system was single-phase, the "idle" core could be connected alternately to each of the outers, between joints and network boxes, thus maintaining a balance on single-phase. When the transfer to the "standard" system took place it would only be necessary to break and remake joints to obtain a balance.

Transformers and switchgear of a type which could be adapted for the "standard" system of supply, could be used on single-phase.

An objection is sometimes put forward to the investment of capital in 4-core cables which cannot be fully utilized while the system is operating on single-phase. The percentage increase in expenditure of laying 4-core cables instead of 3-core cables of equal cross-section per core is small, as can be seen from Table 4.

For the extra expenditure shown in Table 4, a 50 per cent increase in carrying capacity, a 33 per cent decrease in I^2R losses, and a 33 per cent decrease in voltage-drop are obtained immediately the network is changed to the "standard" system of supply, assuming balanced conditions and that all the load is connected between phases and neutral.

(*c*) As stated above, little or no work would be necessary inside consumers' premises in changing an area from the single-phase to the "standard" system. The inconvenience to consumers, therefore, would be very small.

TABLE 3.

Method	Advantages	Disadvantages
(*a*) Single-phase high-tension to single-phase low-tension	Small and simple substation equipment All network fed from one source of supply can be interlinked	Unbalanced h.t. system. Network fed from one centre cannot be interlinked with networks fed from adjoining centres Reduction in stand-by and elasticity of system
(*b*) Delta/double-star ..	Dual supply (3-phase and single-phase) can be obtained from the same source at the same time With a slight adjustment standard 3-phase transformers can be used Can be interlinked to a limited extent with other l.t. sources of supply Good balance on h.t. system	Network fed from one source of supply must be divided into three separate sections, thereby causing difficulty in network design and operation
(*c*) Scott	Can be linked with other sources of supply to a greater extent than (*b*) Good balance on h.t. system	Network fed from one source of supply has to be divided into two separate sections, causing difficulty in network design and operation Non-standard transformers must be used
(*d*) Open delta	Interlinking can take place from networks fed from adjoining centres	Poor balance and power factor on h.t. system Specially designed, expensive transformers required

COSTS AND ECONOMIC ADVANTAGES OF CHANGE-OVER.

It is impossible to give even an approximate figure for the cost per consumer, as this will vary in different districts and depend on the type of property supplied.

The cost per kW based on the maximum demand of an area to be changed over remains fairly constant and the figures given in Fig. 7 have been computed from results

TABLE 4.

Cost per 100 *Yards' Run for Distributor only.*

	3-core, 0·1 sq. in.	4-core, 0·1 sq. in.	3-core, 0·15 sq. in.	4-core, 0·15 sq. in.
	£	£	£	£
Cable	33·8	40·1	42·4	53·3
Laying and jointing	7·5	8·7	9·2	10·8
Excavation and reinstatement ..	25·0	25·0	25·0	25·0
Administration, supervision, etc. ..	7·5	8·3	8·4	8·7
Total cost for distributor only ..	£73·8	£82·1	£85·0	£97·8
Percentage increase..	—	11·2	—	15·1

Cost per 100 *Yards' Run of Low-Tension Network.*

	£	£	£	£
Distributor	73·8	82·1	85·0	97·8
Network boxes, tee boxes, etc. ..	19·5	20·5	19·5	20·5
Services	33·0	33·0	33·0	33·0
Total cost	£126·3	£135·6	£137·5	£151·3
Percentage increase..	—	7·4	—	10·0

obtained from a number of different types of residential and suburban areas.

In these costs no credit has been made for d.c. plant which would have to be removed. If the rectifiers or

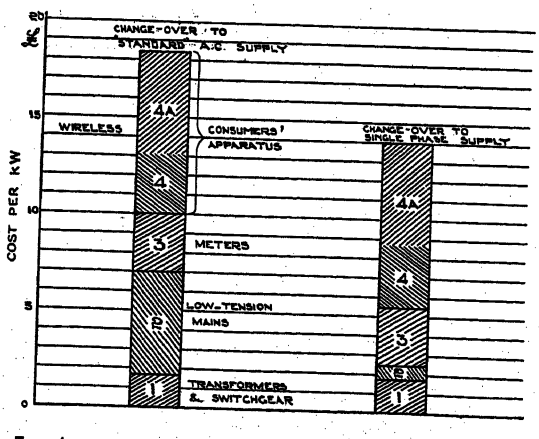


FIG. 7.—Approximate cost per kW, based on maximum demand of change-over in suburban areas.

convertors could be used elsewhere on the same system or sold for use on another d.c. system, then a sum might reasonably be credited to the change-over, which would greatly reduce the total cost.

From an engineering point of view the advantages to be derived from the expenditure shown in Fig. 7 have already been dealt with, but the capital outlay must also be justified from a financial standpoint. Fig. 8 shows approximate maintenance costs for both d.c. and a.c. low-tension distribution per kW per annum, based on maximum demand.

The reduction in maintenance charges on static substations compared with rectifier or rotary substations requires no explanation. The smaller costs for mains and services are accounted for by the freedom from electrolysis on an a.c. system and the large reduction in the number of faults. Records kept over a period of years show the average number of low-tension mains faults per 100 miles of distribution per annum to be 10·8 for a d.c. system and 0·99 for an a.c. system, and the average number of service faults per 1 000 services per annum to be 1·7 on d.c. supply and 0·1 on a.c. supply.

A usual estimate of the rate of increase in the demand for electricity is 15 per cent per annum. This means that the maximum demand of an area will be doubled every 5 years. A considerable proportion of the annual expenditure on a low-tension network must therefore go towards meeting development by increasing the capacity

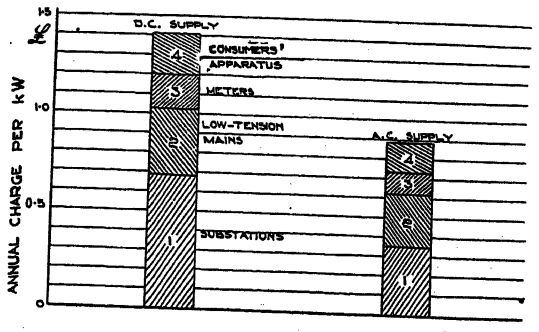


FIG. 8.—Approximate comparative costs per kW per annum, based on maximum demand, for maintenance and repairs on low-tension distribution in suburban areas.

of a system. Fig. 9 shows the approximate cost per kW of laying down a new a.c. centre, compared with the cost of installing a d.c. centre of equivalent capacity.

An examination of Figs. 7 and 9 shows that where it is necessary to increase the capacity of a d.c. system it is cheaper to install an a.c. centre and change over the area to be supplied from it, than to install a d.c. centre of equivalent capacity, assuming that the initial maximum demand would be half the value of the plant capacity installed. Comparative costs are given in Fig. 10.

Alternating-current plant requires less floor space than d.c. plant, and if the maximum demand of a d.c. centre were 75 per cent of its plant capacity it might be considered necessary to double the capacity of the existing plant. Fig. 11 shows comparative costs for doing so by (*a*) extending the building and installing additional d.c. plant, or (*b*) installing a.c. plant and changing over the network supplied from this centre.

In addition to the advantages shown in Figs. 8, 9, 10, and 11, there are others to be derived from changing from d.c. to a.c. supply.

New meters are required as new consumers are connected to a system. The cost of an a.c. meter is approximately 30 per cent less than that of a d.c. meter of corresponding make and capacity. Thus, by changing

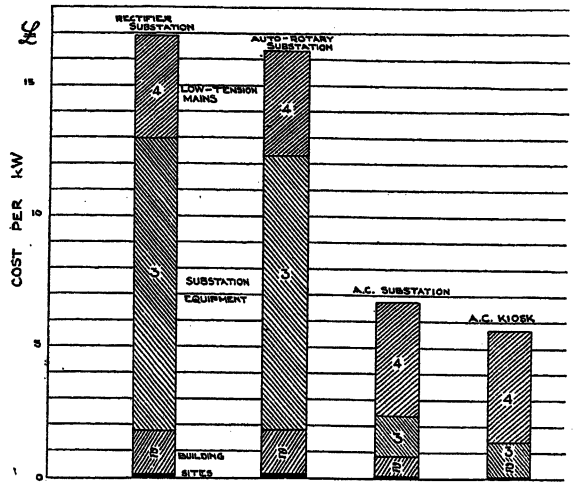
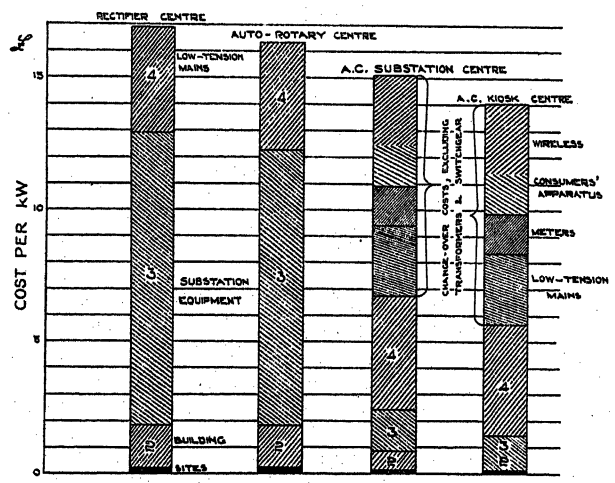


FIG. 9.—Approximate comparative costs per kW of d.c. and a.c. distribution centres in suburban areas.

a system to alternating current a reduction in meter charges is obtained of approximately 10s. for every consumer connected to the supply subsequent to the change-over.



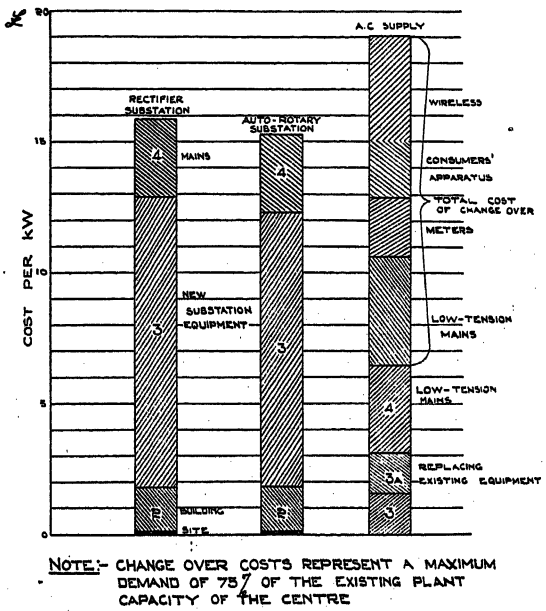
NOTE:- CHANGE-OVER COSTS REPRESENT A MAXIMUM DEMAND EQUAL TO 50% OF THE PLANT CAPACITY OF THE CENTRE.

FIG. 10.—Approximate comparative costs per kW of installing an a.c. centre and changing over an area, with cost of installing a d.c. centre of equivalent capacity in suburban areas.

An increased revenue may result from the use of a.c. meters instead of d.c. meters, because of the greater sensitiveness of the former. Further, the a.c. meter registering kWh is more equitable to both the consumer and the supply authority than the d.c. meter calibrated in ampere-hours.

Figs. 9, 10, and 11 show approximate capital expenditure, but it is obvious that capital invested in plant which may last for 50 years is of much greater real value to an undertaking than a similar sum invested in plant which will answer the same purpose but may only last for 25 years. The life of a d.c. network as compared with that of an a.c. network is therefore a matter which has important financial considerations.

The life of a low-tension network depends to a large extent upon the nature of the soil in which the cables are laid. As a matter of general practice the Electricity Commissioners, in the case of municipal undertakings, allow 25 years for loan repayment on low-tension cables, and if this term be accepted as the period of useful life (free from continuing faults) of a d.c. network, the life of an a.c. system, under similar conditions, would probably be in the neighbourhood of 50 years. Hence



NOTE:- CHANGE OVER COSTS REPRESENT A MAXIMUM DEMAND OF 75% OF THE EXISTING PLANT CAPACITY OF THE CENTRE

FIG. 11.—Approximate comparative costs of doubling the capacity of a centre, by (*a*) installing additional d.c. plant, and (*b*) installing a.c. plant and changing-over in suburban areas.

an undertaking employing a d.c. system would, in all probability, be faced with the necessity of whole or part renewal of its network at the end of the period referred to, whilst the useful and free-from-trouble life of an a.c. network, under the same conditions, could safely be calculated to continue for a further 20 to 25 years. The financial advantage is apparent, and a change-over from direct to alternating current would undoubtedly, after a number of years, result in a large reduction in the capital outlay of an undertaking. Also, the life of transforming plant would probably be more than double that of rectifying plant.

It is interesting to note that some eight years ago a supply undertaking in the North Midlands was faced with the entire replacement of a large section of its d.c. network. In 1923 this section was changed over to alternating current and at the present time is giving complete satisfaction. In this case the total cost of the

change-over was much less than the estimated cost of replacement, and when the change-over was completed the advantages of reduced maintenance and development charges were obtained. While the area was on the d.c. system, faults were constantly occurring, but since the change-over faults have been practically unknown.

Efficiency.—The overall efficiency of a static substation is, of course, higher than that of a rectifier or convertor substation. An approximate comparison is shown in Fig. 12.

Power Factor.—Although the majority of the load in suburban areas would be approximately non-inductive, to reduce the cost given in Figs. 8, 9, 10, and 11, to a common basis a power factor of 0·85 has been assumed.

The small cost of an a.c. distributing centre compared with that of a d.c. centre makes the economic feeding radius of the former much less than that of the latter. The increased distribution efficiency resulting from this smaller feeding radius should more than compensate for the losses due to wattless current.

To summarize the economic advantages of change-over:—

(*a*) *Maintenance and repairs.*—The annual reduction

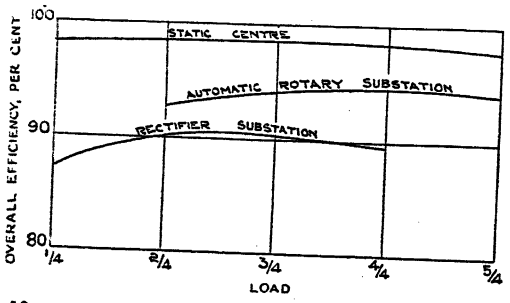


FIG. 12.—Approximate comparative overall efficiency of static, rectifier, and automatic rotary substations for suburban areas.

in maintenance charges forms approximately 3 per cent of the total cost of changing over.

(*b*) *Development.*—On the basis of an annual increase of load of 15 per cent, the total cost of changing over should be recovered in approximately 5 years from development charges alone.

(*c*) *Increased life of networks.*—The reduction in capital expenditure due to the increased life of a network is important, as, in many cases, the price at which the unit of electricity is sold is considerably affected by the annual charge for interest and loan repayment on the capital invested in low-tension cables and plant.

Any one of the above advantages is almost sufficient to justify changing over, and when they are considered collectively there would appear to be no doubt as to the economic advantage of changing over any suburban or residential area.

SUMMARY TO PART 1.

In the opinion of the authors, in suburban or residential areas, from both the engineering and the financial standpoint, it has been clearly indicated that:—

(*a*) Any area at present supplied by direct current should be changed over to alternating current at the earliest opportunity, irrespective of the loading on the d.c. plant or the condition of the networks.

(*b*) Only in exceptional circumstances should any additional d.c. plant be installed.

(*c*) Wherever possible, the "standard" 3-phase system of supply should be adopted.

(*d*) The smaller cost of changing over from the d.c. to the single-phase supply rarely justifies its use, except for small isolated areas, and there it should only be adopted as a temporary measure.

(*e*) The advantages of the a.c. supply and the limitations of the single-phase system will ultimately compel the adoption of "standard" 3-phase 4-wire distribution; therefore, although at present the supply may be by direct current or single-phase alternating current, only 4-core cables should be laid, 4-wire network boxes installed, and, as far as possible, all new switchgear, etc., should be suitable for 3-phase 4-wire supply.

PART 2. CHANGE-OVER IN INDUSTRIAL AREAS AND IN HEAVILY-LOADED CITY AREAS.

SHORT COMPARISON OF D.C. AND A.C. SYSTEMS.

The advantages claimed in Part 1 for a.c. distribution in suburban areas also apply to industrial and city areas, but in giving supply to the latter there are certain disadvantages which are not experienced in supplying the former:—

Power Factor.

At present the majority of a.c. motors connected to a system are of the induction type. These motors, especially when running under their rated output, require from the mains a wattless kVA, and where the proportion of motor load is high this may necessitate the installation of power-factor-correction plant. Fortunately, in many areas, a good proportion of the load is practically non-inductive and tends to minimize the effect of the wattless kVA due to motor load. Consumers are also becoming aware of the advantage of a high power factor, and some supply authorities are introducing preferential terms for good power factor. The result is that, in some instances, consumers are installing synchronous motors or other means of power-factor correction, and, should this practice continue, difficulties resulting from a bad power factor will tend to diminish.

Where power-factor improvement is considered necessary, it is obviously undesirable to install plant for this purpose at each distributing centre, and the authors are of the opinion that this problem should be dealt with from the high-tension side of a system by installing power-factor-correction plant at certain selected master-substations. Comparing individual centres, however, the cost of an a.c. installation, including power-factor-correction plant, is still much less than that of a d.c. installation of equivalent capacity.

In some undertakings traction load supplied from rotary convertors might be used, to some extent, for power-factor improvement.

Stand-by Supplies.

On heavily-loaded d.c. systems, in the event of a

failure of supply secondary batteries can be used. On an a.c. system there is nothing to replace such batteries, and in the past this has been put forward as one of the chief objections to a.c. distribution.

The initial and maintenance costs of secondary batteries are very high and, under present conditions, it is doubtful whether their use is justified on a d.c. system, except under very unusual circumstances.

On an a.c. system, hospitals, theatres, etc., could have duplicate services each supplied from a separate distributing centre. Stand-by supplies would thus be provided except in the case of a complete failure of the high-tension system, which, under present-day conditions, is a very remote possibility. In special cases a system of pilot lighting could be supplied from small private batteries.

Motors.

Until recently the a.c. motor was, in certain circumstances, at a disadvantage when compared with the d.c. motor, but in recent years the design of the former has been greatly improved, and for most purposes it now compares quite favourably with the latter.

The disadvantages stated above are not serious, and when the advantages of a.c. supply, enumerated in Part 1, are considered, there seems to be no doubt as to which is the better system of distribution for industrial and city areas.

Reasons for Change-over.

The standardization of low-tension distribution is even more important in industrial and city areas than in suburban areas, because of the greater amount of apparatus connected to the supply.

The total cost of changing over would be greater than in suburban areas, but, due to the density of the load, the cost per kW based on maximum demand would probably be less.

Where the growth of load necessitates an increase in the capacity of a d.c. system, if it can be shown that the increased capacity can be obtained by changing over to alternating current at a cost not greatly in excess of obtaining a corresponding increase on direct current, then there should be no question as to the advantage of changing over.

Choice of System.

Owing to the type of load and conditions of loading, the single-phase system need not be considered for these areas. The number of motors of large output and the necessity for interlinking between all distribution centres makes the "standard" system, in the opinion of the authors, the only suitable means of a.c. distribution for industrial and city areas.

Many large shops, stores, small factories, and large buildings containing numerous offices, are at present supplied from the low-tension d.c. system, and have a maximum demand varying from 30 kW up to, or even exceeding, 200 kW. It is suggested that any consumer, or any building containing a number of consumers, having a maximum demand of more than 30 kW should be changed over to the high-tension supply. This transfer could take place gradually, starting with the consumers who take the heaviest load, and by this means the low-tension d.c. network would be relieved and enabled to deal with any increase in loads of smaller size. Heavy low-tension feeder losses would also be avoided.

Difficulties are likely to arise in obtaining sites for substations inside consumers' premises, but an a.c. substation, to give a supply to one consumer, requires very little room. In the case of factories and workshops, when it is explained that the existing d.c. plant, which may be obsolete and inefficient, will be replaced by efficient a.c. plant, and that the maintenance charges on the latter will be very much less than those on the former, the consumer would usually find room for a substation and might even be persuaded to pay part of the cost of changing over. Opportunities would also occur to transfer d.c. installations to the high-tension supply when consumers wished to increase their load.

When the increase in low-tension load exceeded the relief obtained from the transfer to the high-tension system, a change-over of small sections of the d.c. network to standard a.c. supply could take place. Gradually the load on the peripheries of the areas supplied from d.c. substations could be transferred to alternating current. The radius of supply of d.c. substations would thus be reduced, and d.c. feeders could be reduced in length and so enabled to deal with increased demand on that portion of the d.c. network nearer the substations. A reduction in low-tension distribution losses and an improvement in voltage regulation would thereby take place.

It would be unnecessary to increase the d.c. converting plant or to lay any additional low-tension d.c. feeders, and as the existing converting plant required replacement the a.c. distribution could be extended and the d.c. system reduced, until finally a complete "standard" a.c. system would be obtained.

The majority of industrial and city areas have been well developed electrically for a considerable time, with the result that where the supply is direct current a very large proportion of the mains are 3-wire.

Many of the existing d.c. feeders consist of 3 single, lead-covered, armoured cables of 1·0 sq. in., 0·5 sq. in., 1·0 sq. in. cross-section and, due to sheath and armour losses, it would be impossible to use these feeders economically for any type of a.c. supply. The existing 3-wire distributors could not be used on two phases and neutral, because of the nature of the load and the density of the loading. Therefore, before changing over a section of an industrial area to alternating current it would be necessary to replace nearly all the 3-wire mains in the section with 4-core mains, or to superimpose a new 4-core network on the existing 3-wire network.

An area remaining on direct current requires new cables to replace old, and to supply new consumers. If all these new cables were 4-core it would materially reduce the cost of change-over. It would also be an advantage if all new power consumers could be prevailed upon, as far as possible, to install wiring and switchgear suitable for 3-phase supply.

Should a high-tension supply in any area be of a frequency other than 50 cycles per second; it might be

necessary to lay new low-tension feeders to meet the increase in d.c. load until the standardization of frequency made it possible to relieve the low-tension network by transfers to the high-tension system. As already mentioned, a type of feeder very often used in heavily-loaded d.c. areas consists of 3 single, lead-covered, armoured cables. Instead of laying this type of feeder, a number of 4-core cables might be laid from the substation to the feeding point, each cable by a different route. By this means a 4-core network suitable for a.c. supply would be built up as shown in Fig. 13. It will be noted that the same section of copper would be obtained by each method. In method 2 the cores of each 4-core cable would be connected together to form one d.c. conductor. Assuming routes 1, 2, and 3, to be of equal length, the total cost of the feeder would only be 30s. per yard more by using 4-core cables than by using the three single cables. Thus, when a change-over to alternating current takes place, a 4-wire network would be obtained at an approximate cost of 10s. per

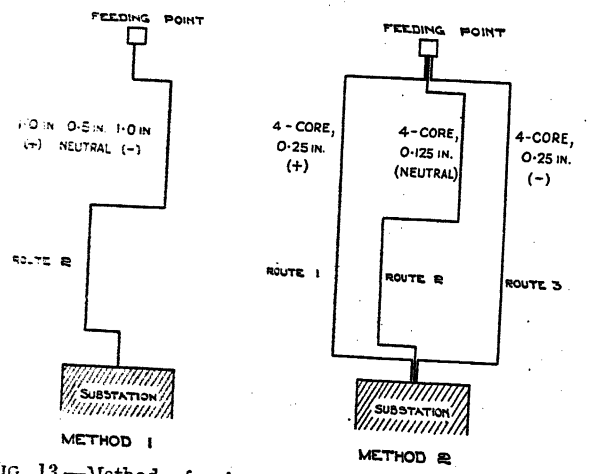


FIG. 13.—Method of using 4-core cables to form one d.c. feeder.

yard. Full use could be made of the 4-core cables on both direct and alternating current, but the three single cables would be practically useless for the latter supply.

COSTS AND ECONOMIC ADVANTAGES OF CHANGE-OVER.

The authors have not at their disposal sufficient information to enable them to put forward actual costs for changing over in industrial or city areas, but although the cost per square mile would be very much higher it is not anticipated that the costs per kW based on maximum demand would exceed those shown in Fig. 7 for suburban areas, for the following reasons:—

Substation Equipment.—The cost per kW for substation equipment would be smaller because of the larger units installed.

Mains.—In areas where the whole of the existing network consisted of 3-wire cables, an entirely new network would be required, and the cost per kW for mains would be in excess of that for suburban areas, but not to such an extent as would appear from a preliminary survey. The density of the load, and therefore the load obtainable per yard run of cable, would be very much higher in industrial and city areas. Further, the rate of change-over would be slower than in suburban areas, and where new mains were required for development and replacement a partial 4-core network could be built up before the change-over.

Meters.—An a.c. meter of 20-ampere capacity costs approximately only 20 per cent more than one of 5-ampere capacity; therefore, owing to the greater load per consumer, the meter cost per kW would be very much less in industrial and city areas than in suburban areas.

Consumers' Apparatus.—In industrial and city areas, such as the authors have investigated, where the load is of a very mixed nature, and where large shops, stores, large buildings containing numerous offices, and small factories and workshops, are connected to the same system, the number of motors and other apparatus which would require to be changed is much greater than in suburban areas, but there is also a great increase in

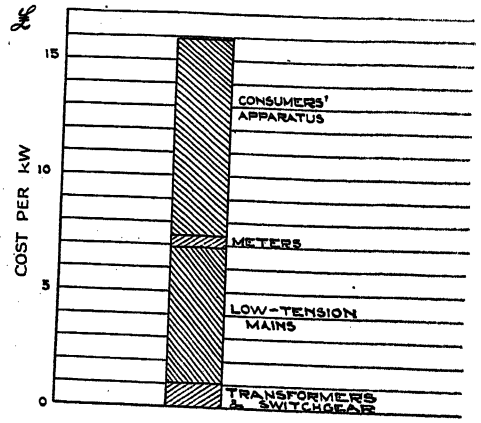


FIG. 14.—Estimated costs per kW, based on maximum demand for changing over in industrial and city areas.

the amount of lighting, heating, and other apparatus which would not require alteration.

An approximate estimate, for changing over in industrial and city areas, of the cost per kW based on maximum demand, is given in Fig. 14.

The advantages resulting from the expenditure shown in Fig. 14 would be similar to those claimed for suburban areas.

Maintenance.—Fig. 8 shows the comparative costs for maintenance and repairs for d.c. and a.c. systems in suburban areas. On account of the density of the load, these costs would be less for both systems in industrial and city areas, but it may be safely assumed that the annual charge per kW would be at least 35 per cent less for an a.c. than for a d.c. system.

The following extracts from a report in a recent issue of the *Electrical Review* (1931, vol. 109, p. 516) are of interest:—"A.C. motors are now replacing d.c. machines for 27 000 drives in the River Rouge plant of the Ford Motor Co. at Dearborn, Mich. Drives of production machines ranging in size from ¼ h.p. to 1 750 h.p., totalling 85 000 connected h.p., are affected. Benefits

from the change include conspicuous reductions in costs of motor and control maintenance, ease of expanding production facilities as they occur in future, greater safety to workmen, reduction of energy losses in distribution lines and in conversions to direct current, reduction of substation operation labour, and the elimination of much connected capacity represented by over-motoring certain drives. The company has been at work on the job for about a year, and now has it about one-half completed. The change has already resulted in a 78 per cent reduction of motor repair labour, for which 120 men are now employed instead of 550 men as formerly." Works such as are mentioned in the above report would include some of the principal features of the distribution system of a supply undertaking, and would represent a change-over in a purely industrial area, where probably 90 per cent of the load would be motor load. It would also appear that the authors' estimate of the reduction in maintenance

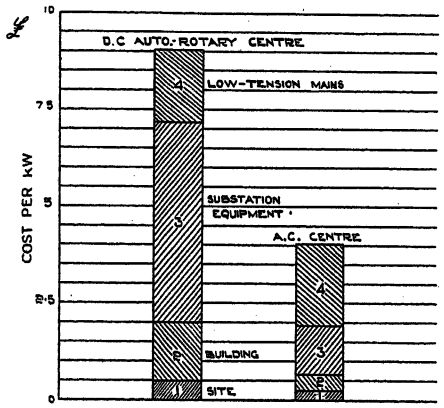


FIG. 15.—Approximate comparative cost per kW for installing d.c. and a.c. centres in industrial and city areas.

charges resulting from a change-over is very conservative. The report further indicates the advantages to be obtained by an industrial consumer from a change-over to a.c. supply, the importance of which is obvious, both from the individual and the national point of view.

When a company of the undoubted business acumen of the Ford Motor Co. undertake the entire replacement of their plant to obtain the advantages of a.c. supply, there appears to be no necessity for further comment.

Development.—The approximate comparative costs for installing a.c. and d.c. centres in industrial and city areas are shown in Fig. 15. To obviate the necessity of introducing labour charges it has been assumed that the d.c. centres would be equipped with automatic rotary plant.

When a new centre is laid down to meet the growth of load on a well-developed d.c. system, it is usual to install plant with a capacity of approximately double the initial maximum load expected, and so provide stand-by facilities and make provision for future development. Under these conditions the cost of installing an a.c. centre and changing over the network to be supplied from it would not be greatly in excess of the cost of installing a d.c. centre of equivalent capacity, as shown in Fig. 16.

To reduce to a common basis the comparative costs given in Figs. 14, 15, and 16, a power factor of 0·8 has been assumed. This power factor is probably considerably lower than would be met with in actual practice.

The advantages of reduced meter charges, reduction in capital expenditure due to the longer life of an a.c. network, and increased efficiency, already detailed in Part 1 for suburban areas, would also be obtained from a change-over in industrial and city areas, and when these are considered in conjunction with the reduced

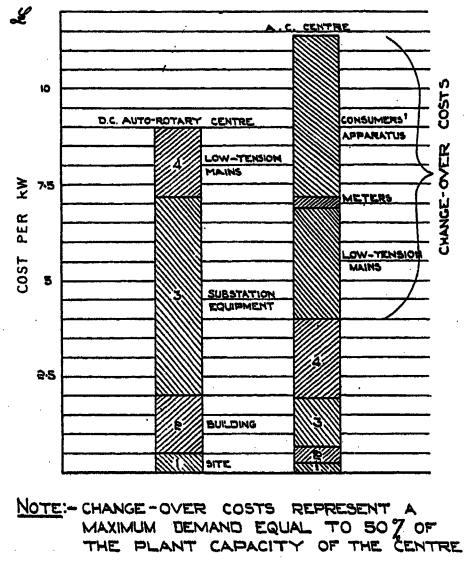


FIG. 16.—Approximate comparative costs for installing in industrial and city areas (*a*) an a.c. centre and changing-over network to be supplied from it, and (*b*) a d.c. centre of equivalent capacity.

maintenance and development charges there seems no doubt as to the financial advantage to be derived from changing over.

SUMMARY TO PART 2.

The authors are of the opinion that the investigations carried out for industrial and city areas indicate that:—

(*a*) There is ample justification for the change-over of any industrial or city area, but the rate of change-over should be much slower than in suburban areas.

(*b*) The only a.c. method of low-tension distribution suitable for industrial and city areas is the "standard" 3-phase 4-wire system.

(*c*) The existing d.c. network should first of all be relieved by transferring, where possible, low-tension consumers with a maximum demand of over 30 kW to the high-tension supply.

(*d*) When the increase in low-tension load exceeds the relief afforded by (*c*) a new 4-core network should be superimposed on the existing 3-wire d.c. network, and a gradual change-over to alternating current should take place.

(*e*) No new d.c. plant should be installed, and as the existing plant requires replacement the a.c. system should be extended and the d.c. system reduced.

(*f*) All new cables should be 4-core, and only 4-wire network boxes should be installed.

PART 3. GENERAL.

Consents.

Before a change-over can be commenced, it is necessary to obtain the consent of the appropriate authority, and the undertakers must make application to the local authority and/or the Electricity Commissioners, stating the nature of the change it is intended to make. Usually accompanying this application there must be a complete list of all the streets or roads affected and a map or maps showing their relative positions. This procedure is comparatively easy to follow when only a small area is to be changed over, but when extensive proposals are involved it may become cumbersome.

The application may cover an area parts of which may not be changed over for two or three years after the date of application, and during that time it may be necessary to give a d.c. supply to streets or roads which were not supplied at the date of application and therefore not scheduled.

A better method, sometimes adopted, is to schedule wards or districts, or parts thereof, instead of specifically mentioning each particular street or road.

Before the Electricity Commissioners give their consent, the intention to change over must be advertised in the local Press for a minimum period of one month, so that any consumer who objects to the change-over may have an opportunity of making representations to the Commissioners.

The Commissioners' consent usually contains conditions which provide that, unless otherwise agreed, the undertakers shall at their own expense carry out the necessary alterations to consumers' existing apparatus to suit the altered system and pressure of the supply, or pay to each consumer injuriously affected by the alteration of system and pressure such sum as may be agreed upon, or, in default of agreement, as may be determined by an arbitrator to be the reasonable cost incurred by the consumer as the result of the alteration; provided that in any case where notice of their intention to carry out the change of system and pressure is served by the undertakers on a consumer not less than one month and not more than six months prior to the date fixed by the undertakers for carrying out the alterations, no liability shall attach to the undertakers in respect of apparatus installed by the consumer after the service of such notice, unless otherwise agreed between the undertakers and the consumer.

Procedure of Carrying out Change-over.

The change-over programme covered by the application to the Electricity Commissioners may require two or three years to complete, and a preliminary survey should be made, the area affected being divided into sections, preferably such that each section will be supplied from a separate a.c. centre. An approximate time-table should then be prepared so that preparations for the change-over may go forward in correct sequence.

New centres may be required, and, if the necessary sites have not been obtained, arrangements should be made to acquire them.

As a result of the Press notice, stating the undertakers' intention to change over, a large number of inquiries as to the date of the change-over would usually be received from consumers in the areas affected, and immediately the consent of the Electricity Commissioners is obtained it would be advantageous to prepare a standard reply, so that the approximate date may be inserted in each case.

Another circular, requesting consumers not to purchase any apparatus unsuitable for use on a.c. supply, without reference to the electricity department, should be prepared and, as the opportunity offers, sent to all consumers included in the first 18 months of the programme. New consumers in areas which are likely to be changed over within 18 months should also receive this circular when they make their application for supply. In some cases it may be possible to make arrangements to defer the purchase of apparatus which would be costly to change over, or to arrange for the hire of d.c. apparatus until such time as a.c. supply is available.

In changing over any particular area from one distribution centre close co-operation is necessary between the various departments of a supply undertaking, such as mains, substations, meters, and consumers. These departments must work together to ensure that the actual change-over takes place with the least possible inconvenience to consumers and the minimum of risk to the continuity of supply.

A model procedure for changing over the supply area of one distribution centre is given below:—

(1) A plan, preferably to a 1/2500th or similar scale, is prepared showing all the distributors and services in the area. The 4-core and 3-wire mains are shown in different colours, and also the twin, 3-wire, and 4-wire services.

(2) With the aid of the service plan and the consumers' record cards, a loading plan, also to 1/2500th scale, is prepared, showing the mains in their respective colours, 4-wire and 3-wire network boxes in different colours, the estimated load in amperes on each section of cable, and all motor loads above 1 h.p.

(3) A preliminary lay-out for a.c. supply is prepared and an estimated cost obtained.

(4) At a conference between representatives of the mains and consumers' departments the area is sectionalized (any one continuous length of distributor representing one section), and a sequence of change-over agreed upon for the area.

(5) (*a*) The service plan is then transferred to the consumers' department and representatives visit each consumer in accordance with the sequence previously agreed upon. Notices are delivered, stating the undertakers' intention to change over. On these notices, which are in duplicate, a space is provided on which is entered an inventory of all the apparatus connected to the supply. The consumer's signature is then obtained, and one copy of the notice is left with the consumer and one retained for departmental use. The change-

over must be completed within six months of the serving of this notice, and the undertakers are not responsible for the alteration of any further apparatus installed. Any new consumers connected to the supply before the necessary for the operation of the consumers' installations on a.c. supply is ordered from the manufacturers.

(*b*) The loads obtained from the record cards are checked with the connected loads as shown by the

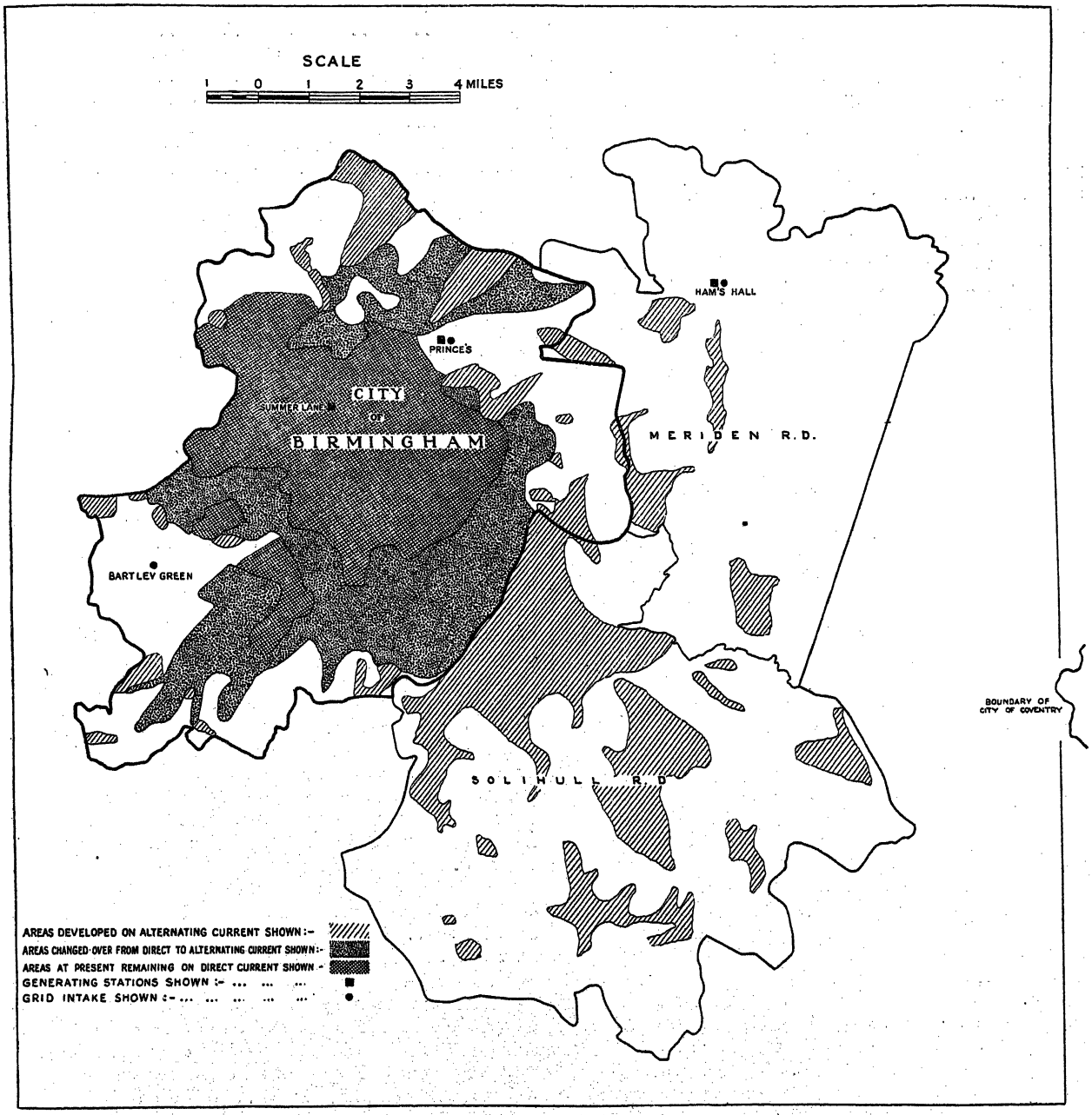


FIG. 17.—Low-tension distribution areas of the City of Birmingham Electric Supply Department, 1931.

actual change-over takes place must also be served with a notice and their services entered on the service plan.

(*b*) The necessary substation equipment is ordered and the meter department informed of the number of consumers to be changed over, so that sufficient a.c. meters may be available.

(6) (*a*) As the inventories are obtained the apparatus inventories, particularly with regard to motor load, and the network is finally re-designed for a.c. supply. The loading plan is converted into a "balancing" plan, showing, in the manner indicated in Figs. 4 and 5, the respective phases on which the cores of the 3-wire mains will operate. The new cables necessary, the network boxes to be replaced or converted, and the services to

be transferred or relaid, are also shown on this plan. The completed plan, or a copy thereof, is sent to the representative of the mains department who is to carry out the actual change-over.

(7) When the substation equipment has been installed, the new mains laid, network boxes altered, services relaid or transferred, and the meters and consumers' apparatus obtained, a conference is held and representatives of the various departments decide upon the dates on which the various sections of distributors in the area will be changed over.

(8) A notice is sent to each consumer about one week previous to the date agreed upon, informing him that the system of supply will be altered on a certain day, and that his supply will be discontinued between certain hours on that date.

(9) On the day previous to the change-over all the a.c. meters and new consumers' apparatus is delivered to the consumers' premises.

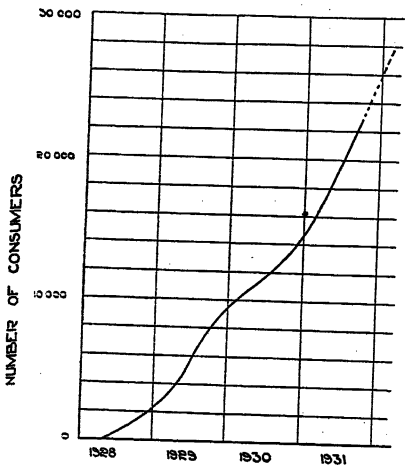


FIG. 18.—Approximate rate of change-over in City of Birmingham.

(10) The actual change-over is then carried out. The section or sections of distributor agreed upon for that day are dealt with. Soon after the d.c. supply has been discontinued, the distributors can usually be made alive with alternating current and a supply given to consumers as their new meters are installed and apparatus altered.

(11) It is important that the change-over of the supply area of one distribution centre, once started, should be completed as soon as possible. Three sections can usually be changed over in one week by arranging the change-over for alternate days. The intervening days are then available for clearing away meters and surplus apparatus. By close co-operation and attention to essential details as many as 240 consumers have been satisfactorily changed over on one section of distributor in one day.

(12) Some time after the completion of the change-over, the consumers are notified that the internal work has been duly completed, and an acknowledgment is ...ally obtained from each consumer stating that the ...nge-over has been carried out to his or her satis-...ion.

The map in Fig. 17 shows the low-tension distribution areas of the City of Birmingham Electric Supply Department. The approximate numbers of consumers in these areas are as follows:—

Approximate number of consumers on d.c. supply	58 000
Approximate number of consumers changed over from d.c. to a.c. supply	28 000
Approximate number of consumers connected to the a.c. system in areas developed on a.c. supply and in areas that have been changed over	32 000
Total number of low-tension consumers ..	118 000

Fig. 18 shows the approximate number of low-tension consumers changed over each year from d.c. to a.c. supply, in the City of Birmingham, during the last few years.

ACQUISITION OF SITES AND REMOVAL OF RESTRICTIVE COVENANTS.

A change-over from direct to alternating current necessitates the installation of a greater number of substations, and owing to the small feeding radius of an a.c. centre the position at which a site is required is restricted to a comparatively small area.

The obtaining of sites is becoming a matter of increasing difficulty, particularly in built-up areas which have been developed on direct current and where no provision, suitable for the lay-out of an a.c. system, has been made for development.

The area required for a substation is, in the majority of instances, too small to be an attractive proposition to a potential vendor, who becomes an unwilling seller and invariably puts an extortionate value on the land or refuses to sell.

In some cases it is impossible to obtain land anywhere near the ideal position for a site, while in other instances a much larger area has to be purchased than is actually required.

Restrictive covenants sometimes imposed upon land during the last century, often prevent the acquisition of suitable sites. Even where an owner is willing to sell on terms acceptable to an undertaking, the latter may be reluctant to purchase, as such covenants as those mentioned above may entitle some person or persons who have no direct interest in the sale of the site to bring an action for damages against the undertaking.

Town-planning regulations and other such impediments are frequently met with, and if the full advantage is to be obtained from a change-over to a.c. supply it seems essential that supply authorities should be able to obtain sites where necessary, for the position of substations has a very important bearing on the distribution efficiency of a system.

The necessity appears to be obvious for facilities to be afforded for compulsory purchase by means of straightforward reference to an arbitrator, or to a Government body.

Much has already been written on this subject and,

in the opinion of some legal authorities, certain powers are available under the Electric Lighting Act, 1909, and the Public Works Facilities Act, 1930, but the urgent need appears to be for more definite, speedy, and direct powers.

Supplementary Explanation of Costs.

The costs given in Part 2 for the change-over in industrial and city areas are approximate estimates, but those given in Part 1 for suburban areas were obtained from expenditure incurred during the year ending December 1930. All these costs are, of course, based on the maximum demand of a distribution centre the area supplied from which is being changed over, and they bear no relation to the maximum demand of any particular type of apparatus in the area. Thus, an electric cooker with a maximum demand of from

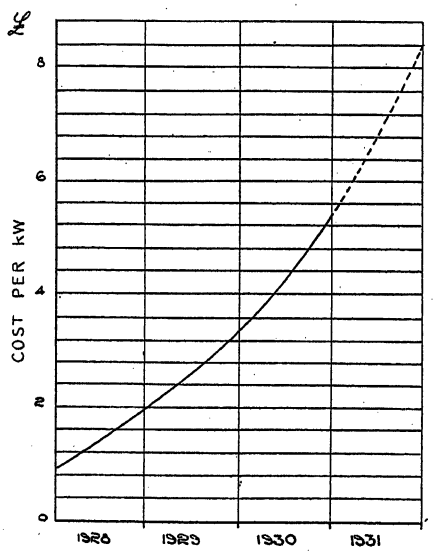


Fig. 19.—Approximate change-over costs per kW for wireless apparatus only, based on the maximum demand of the area being changed over.

3 to 6 kW requires no alteration and costs nothing to change over, but the cost of changing over wireless apparatus, based on the maximum demand of wireless apparatus alone, would probably be over £400 per kW.

Although many supply authorities do not undertake, during a change-over, the alteration or replacement of wireless apparatus to suit the altered system of supply, all the costs and comparisons given in Part 1 for changing-over in suburban areas include the expenditure necessary for altering or replacing this type of apparatus. In order to give a relative result in cases where it is not intended to deal with wireless apparatus, the expenditure relating thereto has been shown separately in Figs. 7, 10, and 11, and can be eliminated if necessary.

In the case of a small wireless set supplied by a d.c. eliminator the current required may not be sufficient to start the d.c. meter. Therefore this service may be given free for a considerable portion of the time during which such a set is in use, and it does not seem reasonable that the undertakers should be expected to incur expenditure to adapt, for use on the altered system of supply, apparatus from which they have received little or no revenue.

Fig. 19 shows the increase in the approximate cost of changing over wireless apparatus during the last few years, and indicates that any supply authority undertaking the alteration or replacement of this type of apparatus should complete the change-over of their suburban areas at the earliest possible date, otherwise the increasing cost year by year may become a serious obstacle to changing over and therefore to the development of electricity supply in these areas.

Change-over Concurrently with Change of Frequency.

Some of the low-tension d.c. distribution centres of certain supply undertakings receive high-tension a.c. supply at a frequency of 25 cycles per second. This frequency will of course be altered to 50 cycles per second by, and at the expense of, the Central Electricity Board, and an opportunity thus occurs to change over to a.c. supply the low-tension d.c. networks supplied from some of these centres.

By carrying out the low-tension system change-over in conjunction with the change of frequency the inconvenience and total cost would be considerably less than would be the case if the change of frequency were carried out first and the low-tension change-over at a later date.

During the change of frequency at a distribution centre equipped with automatic rotary or rectifier plant, it might be necessary to erect a temporary building, install temporary plant, remove, rewind, and re-install the existing plant, remove the temporary plant, and take down the temporary building. The whole of the cost of these alterations would, of course, be chargeable to the Central Electricity Board.

The expenditure, excluding the cost of changing over the low-tension network, would obviously be very much less if transformers and low-tension a.c. switchgear were installed, the low-tension network changed over to alternating current, and the d.c. plant dispensed with when the change-over was completed.

The authors understand that, should an undertaking decide to carry out a low-tension system change-over in conjunction with the frequency change at any distribution centre, the Central Electricity Board may allow to the undertakers a sum equal to a certain proportion of the estimated cost of altering the d.c. converting plant in this centre to suit the altered frequency of supply, and this sum may be credited towards the cost of the low-tension change-over. It is therefore to the advantage of both the Central Electricity Board and supply undertakings that the change-over of low-tension d.c. networks should, where possible, be carried out concurrently with a change of frequency.

CONCLUSIONS.

The authors are of the opinion that their investigations indicate that not only are engineering and technical advantages to be derived from a change-over to low-tension a.c. supply in suburban, industrial, and city areas, but that a change-over in these areas is essential for economic reasons.

The expenditure necessary for change-over and de-

velopment must vary, owing to local conditions, and must depend upon the type and density of the load, the type of plant and apparatus installed, and the engineering practice adopted, but it is not claimed that the various costs put forward in the paper would apply to all supply undertakings or to any one undertaking. These costs are for comparative purposes only and, although they are only approximate, an endeavour has been made in all cases to maintain a just comparison, and the authors feel that sufficient accuracy has been obtained to show clearly the financial advantages to be derived from changing over in any area.

It has been assumed that the d.c. voltage prior to a change-over would be sufficiently near to the " standard " a.c. voltage to obviate the necessity of altering any apparatus because of an alteration in the voltage of the supply. The problem of the standardization of voltage has been fully dealt with in a previous paper by Messrs. Beard and Haldane,* and the present authors are most decidedly of the opinion that where a change of the system of supply takes place, only the " standard " a.c. voltage of 230 volts between phase and neutral should be adopted.

* *Journal I.E.E.*, 1927, vol. 65, p. 97.

The advantages to be obtained from a change-over from low-tension d.c. supply to low-tension a.c. supply would appear to compare favourably with the benefits which, it is claimed, will be derived from the national standardization of frequency, and the authors are of the opinion that the standardization of low-tension distribution is also a national rather than a local problem.

ACKNOWLEDGMENTS.

The authors wish to express their indebtedness to Mr. F. Forrest, Chief Electrical Engineer of the City of Birmingham, for permission to publish the departmental information which has been included in this paper, to those of his staff who have so readily given their assistance, and to the chief and assistant engineers of the other supply undertakings who have rendered information which has materially assisted in the preparation of the paper. They also wish to acknowledge the valuable assistance received from Prof. W. Cramp of Birmingham University, principally regarding the effect of alternating current on the sheath and armour losses of single lead-covered and armoured cables.

DISCUSSION BEFORE THE INSTITUTION, 31ST MARCH, 1932.

Mr. L. Romero: The paper and the discussions to which it will give rise will help to focus attention on the subject of change-over, and may be the means of convincing many engineers of the wisdom of changing their distribution systems over to alternating current. I changed over the first section of a residential-area d.c. network to a single-phase 3-wire a.c. system about nine years ago, and the following year we obtained the sanction of the Electricity Commissioners to change over the whole of our system to single-phase 3-wire alternating current in the residential districts and to 3-phase alternating current in the central and industrial areas. That work has been going on steadily ever since, and it is now almost complete in suburban areas and well advanced in central areas. While I am in full agreement with the authors as to the desirability and economic advantage of changing over d.c. networks to alternating current, I cannot altogether agree with them when they state that the limitations of single-phase supply will ultimately lead to the adoption everywhere of the " standard " 3-phase 4-wire system. If we could ignore the expense I would agree, chiefly for reasons of standardization, as to the desirability of a universal 3-phase 4-wire supply; but where one has in a residential area a well-developed network of 3-core cables, in a large proportion of which the mid-wire is of only half the cross-section of the outer, it is very costly to change over to a 3-phase 4-wire system, as the only satisfactory way of doing so is to replace the whole of the main 3-core distributors by 4-core cables. With a balanced load the conductor losses and voltage drops of 3-core cables are both increased by 50 per cent when the cable is used on a 3-phase 4-wire instead of on a single-phase 3-wire system. Further, if—as is the case in a great many old 3-wire distributors—the mid-wire is of only half the cross-section of the outer, the losses and the voltage-drops are increased by 100 per cent. There must therefore be some strong counter-advantages to make it justifiable to change over to the 3-phase 4-wire system and sustain this heavy loss. In addition to the question of energy loss, there is the difficulty of maintaining the declared voltage at consumers' premises. In favour of the 3-phase 4-wire network the authors state that when a new transformer substation is installed it is just as easy to run 4-core as 3-core l.t. feeders: although this is true, l.t. feeders are nevertheless an undesirable feature. It is most economical to distribute as far as possible at high tension, and in my opinion the ideal l.t. network should consist of a system of large distributors all of the same size. If this idea were adopted it would be possible to install a transformer substation almost anywhere on the network and connect it direct without employing l.t. feeders. In 1927 Messrs. Beard and Haldane* strongly expressed this same view. The need for l.t. feeders on the authors' system is due either to the fact that their distributors are rather small, or to their preferring a large size of transformer substation. So far as a consumer in a residential area is concerned, there is no difference between single-phase and 3-phase distribution. The single-phase supply is perfectly standard for him, and the lack of standardization is only felt by the supply authorities in that they have to buy 3-core as well as 4-core cables and Scott transformers (or some other non-standard type) as well as the standard transformers. In actual practice, however, this disadvantage has not proved very serious. There is the further disadvantage that if there is an existing single-phase 3-wire supply in one part of the area and a 3-phase 4-wire system in another part, it is impossible to interconnect the whole of the l.t. network. This also has proved no great objection in practice. As the authors

* *Journal I.E.E.*, 1927, vol. 65, p. 97.

point out, faults occur so rarely on low-tension a.c. networks that the need for interconnecting is not strongly felt. A small objection to changing over residential areas first to a single-phase and then to a 3-phase supply is that it will necessitate a double change of any medium-size motors there may be on the system. The authors give some relative figures for mains faults on d.c. and a.c. networks, and it would be interesting if they could state the comparison between direct and alternating current so far as multi-core and armoured cables of modern type are concerned. In my experience d.c. faults with cables of that type have been extremely rare, the great majority of troubles on d.c. networks having arisen from the use of single-core cables. The use of single-core cables for l.t. distributors was generally abandoned some years ago, but there must be a considerable mileage of that type of distributor still in use. We in Salford have changed over a number of distributors consisting of single-core plain lead-covered cables, with quite satisfactory results. As a matter of fact, the increased voltage-drop and loss associated with alternating as compared with direct current is relatively small, provided the single-core cables are laid fairly close together, as they are on solid-laid systems. In discussing the costs and economic advantages of change-over, the authors state (page 744): "A usual estimate of the rate of increase in the demand for electricity is 15 per cent per annum. This means that the maximum demand of an area will be doubled every 5 years." I am sure that the authors do not really mean to suggest that the maximum demand on a system will be doubled every 5 years, because if it were we should have 32 times our present maximum demand in the short space of 25 years. I cannot agree with their contention that the best method of correcting low power factor is to install power-factor correction plant on the high-tension side at certain selected master substations. The best place at which to correct power factor is at the load on the consumer's premises, and the nearer one approaches to the power station the smaller will be the proportion of the distribution system which will benefit by the power-factor improvement. The benefits consist not only in an increased load-carrying capacity of the distribution system due to the reduction of wattless current, but also in improved voltage regulation. We in Salford have minimized the disadvantage of the low power factor of a.c. systems by financially interesting our large power consumers in the maintenance of a good power factor. The results of this method have been so satisfactory that up to now we have not had to take any other steps to improve the power factor. I should like to draw attention to a mistake in Fig. 4, which shows a method of feeding 3-phase 4-wire current through three 3-wire distributors with the idea of reducing the voltage-drop and the loss. The method appears to me to be based on a misconception of what is possible in the way of passing alternating current through armoured cables. The current vectors 4, 5, and 6, indicate that a rather heavy unbalanced current would pass through each of these armoured cables, but this would produce an impracticably large voltage-drop, and in fact the current in the neutral would be, not half of, but equal to, the current in the outers in each 3-core cable. No advantage would be gained by such a method of connection, i.e. the voltage drop and loss in the cables would be the same if junction 7 were abolished and the 3-core distributors were jointed straight through from junction 8 to junction 9. The authors deduce from Fig. 4 that—assuming balanced conditions and uniform loading, and provided the neutral conductor is of the same cross-section as the phase conductors—the I^2R loss on the 3-wire mains would be only about 14·3 per cent* less on the single-phase than on the "standard" system. So far as I can make out, however, the loss on the 3-phase 4-wire system would be 50 per cent greater than on the single-phase 3-wire system, and this is a strong reason for retaining the latter. At the beginning of the paper the authors make a comprehensive statement of the relative advantages to the supply authority of a.c. as compared with d.c. distribution. What we have to consider, however, is the advantage to the consumer, because any advantage to the authority which is not shared by the consumer cannot be regarded as real. The advantages enumerated by the authors all benefit the consumer by cheapening his supply of electricity. All the other advantages of alternating current to the consumer either cheapen his apparatus or improve or extend the service which electricity will give him. The following are a few of these. (*a*) Cheaper, more robust, and more reliable motors; (*b*) safe and efficient transformation of voltage by static transformers, which have a large variety of uses; (*c*) safe and more efficient operation of wireless sets; (*d*) greater ease of interrupting the circuit, owing to the periodic occurrence of zero points on current waves (this reduces fire risks and cheapens certain kinds of apparatus); (*e*) easy electrical time-keeping by synchronous clocks; and (*f*) more convenient supply for neon tubes (alternating current is essential for certain types of medical apparatus).

Mr. W. M. Mordey: The paper begins, continues, and ends, on a note of condemnation of direct current for all purposes and under all possible conditions. It suggests that however good and economical a d.c. supply may be, there are no conditions where it ought not to be changed to alternating current. I do not share that view. I even suggest that there are already signs that in the future direct current, not alternating current, will prevail. The authors very properly emphasize the importance of high efficiency of distribution, which they consider to be as important as high efficiency of generation and transmission. I do not, however, agree with their view that high distribution efficiency can only be attained by the use of alternating current, and in support of my opinion on this point I will refer to a case where I was called upon to advise regarding the 3-wire 500/250-volt d.c. system of a little town abroad. The owners of the generating station, which was in the middle of the town, were strongly advised to change over to alternating current. No other supply was available within hundreds of miles, the station was running quite well, fuel was cheap on the site, and the loss in distribution was only about 16 per cent. In order to compare these results with actual figures for this country I examined the Electricity Commissioners' published statistics for 1929—the latest then available. I found

* Corrected for the *Journal*.

that there were over 40 systems in this country working under about the same conditions as those of the foreign town in question; about half had d.c. systems. The average distribution losses for d.c. and a.c. systems were 17·3 and 20·5 per cent respectively. What becomes, then, of the authors' statement that a change-over to alternating current ensures a much higher distribution efficiency. As regards Fig. 12, the curve for a.c. substations shows an overall efficiency of 97 or 98 per cent, but it only deals with large loads. I suggest that the important part of such efficiency curves is the low-load end, as the heavy loads are only on for a short time in each day. Would not Fig. 12 be more useful if the curves were continued down to zero?

Mr. R. W. Steel: While I agree with the authors that where a change-over takes place from direct to alternating current the ultimate aim should be to have a standard 3-phase 4-wire network, the final choice of this scheme must depend principally upon financial considerations. In the case of small undertakings particularly, capital charges must be kept down, and the cost of replacing 3-wire mains by 4-core cables is apt to be excessive. Full use must therefore be made of existing 3-wire cables, and the losses and voltage-drop in the neutral caused by changing over to the authors' "standard" system in many cases compel the adoption of a single-phase supply. The only mode of 3-phase to single-phase transformation that should be considered is the delta/double-star method, because this gives both a single-phase and a "standard" 3-phase system. Further, the transformers can be reconnected at a later date so that both star windings give a standard 3-phase supply. When additional feeders are required for the network it is an advantage to use 7-core cables. In any case, even for a standard system the network has to be split up into three sections in order to obtain a good balance, as is shown in Fig. 4. The cost of 7-core 0·15-sq. in. plain lead-covered cable is approximately 12 per cent less than that of 4-core 0·3-sq. in. cable, but it must be remembered that the neutral of the 7-core cable is only half the size of that of the 4-core cable. The neutral can, however, be provided with twice the cross-section of the outers, and this suggestion has actually been adopted. Such an arrangement enables the feeders to be used later on when the system is finally converted to a "standard" one. While the cost of such a cable would probably be slightly more than that of a 4-core feeder, when all the subsidiary charges are taken into consideration the percentage increase is very small. In fact, a 7-core cable with a double-size neutral might cost slightly less than a 4-core cable of equivalent cross-section. The advantage of a 7-core feeder is that it makes a 3-phase 4-wire supply available, and if any new distributors are required along its route they can be tapped off and a "standard" 3-phase supply given. If, however, the district develops, all new distributors should be of the 4-wire type, supplied by 4-core feeders.

Mr. J. W. J. Townley: I suggest that those who have charge of the work of changing over should give careful consideration to the organization of the means for carrying it out. Some 10 years ago, in an early change-over scheme in which I was interested, the greatest amount of trouble was met with during the actual process of changing over, and the part of the paper which deals with this matter might with advantage be amplified. I am interested in the question of the reduction of distribution faults due to changing over from direct to alternating current, and in this connection I should like to know the probable life of our present distribution systems consisting of paper-insulated lead-covered cables, both on alternating and on direct current. The authors refer to a case where the distribution system changed over was on the point of being replaced owing to frequent faults, which were eliminated by substituting the a.c. supply; I should like to know what sort of system that was, and its age, because the information might throw some light on the probable life of a modern distribution system. Restrictive covenants often lead to difficulty in the acquisition of substation sites, but such covenants can now be removed by the authority interested obtaining Parliamentary powers. I believe that powers removing restrictions of this kind will, before very long, be embodied in a "General Powers" Bill relating to electricity supply. With regard to the acquisition of substation sites, I suggest that we should consider the utilization of positions on the roofs of large buildings in cities and congested areas.

Mr. H. Brazil: There is, I think, general agreement that alternating current is the best type of supply for newly-developed areas, and also that where the cost of the alteration is reasonable existing d.c. supplies should be changed over to alternating current. When, however, we consider the central parts of large towns or cities where there has been a d.c. supply for many years and where the load is very heavy, the difficulties of the change-over become enormous. There will almost certainly be a large amount of electrically-operated printing machinery connected, and the cost of adapting this plant to alternating current would be prohibitive. In many cases the d.c. mains consist of single-core lead-covered cables, and although—as Mr. Romero mentioned—these can be used on an a.c. supply, he must be referring to small-section cables only, as I am convinced that it is quite impracticable to change over a system consisting mainly of 1-sq. in. section lead-covered cables. I have in mind a system in the City of London where a d.c. supply has been given for over 30 years, and which has a large number of newspaper printing-machines connected to its mains. The feeders and distributors are nearly all 1-sq. in. paper-insulated lead-covered cables, and a large number of lead-covered and armoured services are installed. The mains were originally laid for a 3-wire 200-volt system, but shortly afterwards a 3-wire 400-volt supply was substituted. The section of copper in the distributors is therefore very great for a 400-volt system, and it is probable that the existing load could be increased 6 to 8 times without necessitating any increase in the size of the distributors, although, of course, additional feeders would be required. In this case, if a change to alternating current were contemplated the whole of the mains and plant in the substations would have to be scrapped, and an entirely new system of a.c. mains laid. Apart from technical difficulties, this is quite impossible from the financial point of view. In my opinion the correct procedure is to continue to develop the d.c. supply until the load on

the distributors approaches the maximum, and then to superimpose a 4-wire a.c. network in those parts where assistance is needed.

Mr. R. A. Chattock: With regard to Mr. Romero's criticism of the use of 4-wire l.t. feeders from large substations for a.c. distribution, such feeders are necessary because they have to feed into existing 3-wire distributing mains, and also have to be connected at certain points with 4-wire feeders from small substations. Where the network is laid out *de novo* with 4-wire distributors there is no need to run 4-wire feeders, as the transformers can be placed wherever necessary and can feed into the existing 4-wire distributing mains in the ordinary way. Turning to the question of the use of d.c. supplies in the large cities, the centre of the City of Birmingham, for example, is honeycombed with 1-inch feeders, and I cannot see that it will ever be possible to dig all these up and replace them by a.c. cables; the change-over would involve too much disturbance and financial loss. On the other hand, it would be quite easy to superimpose an a.c. network over the centre of the city, and connect to it those consumers whose installations could easily be adapted to the new type of supply. This would relieve the d.c. network and render its extension quite unnecessary. As regards power-factor correction, while it would be advantageous to effect this on consumers' premises, such an idea is far too elaborate for the supply systems of large cities. In Birmingham the power factor is corrected on the h.t. feeders to substations only, as these are generally loaded up to their full capacity. This method gives the most economical utilization of the available copper. A lower power factor on h.t. distributors supplying large consumers does not seem to matter very much, as the copper in these is rarely loaded to its full capacity.

Mr. H. A. Campbell: While I agree that in general no type of supply is better suited to the purposes of secondary distribution than the 3-phase 4-wire system, I do not think that such a supply is best in every case. In suburban districts, for instance, it is hardly necessary to erect 3-phase transformers and lay out a 4-wire system, as very often the single-phase system meets all the requirements. In Jamaica we have been successfully using the open-delta 5-wire system in some districts where we have 3-phase motors, notwithstanding certain disadvantages associated with this type of supply. It is very elastic where the two voltages of the installed apparatus bear the ratio 1: 2, as it provides 3-phase supplies of 110 and 220 volts, single-phase of 110 and 220 volts, and 110/220-volt 3-wire single-phase. Overhead lines are employed throughout, and the difficulties encountered are not so great as when underground cables are used. In America the 3-phase 4-wire system is being extensively adopted for general-purpose secondary underground networks, but American engineers are meeting with the difficulty that whereas this system gives voltages which are in the ratio of $1:\sqrt{3}$, all their apparatus is designed for voltages in the ratio of 1: 2. On motor circuits they are using auto-transformers to raise the voltage to the correct value.

Mr. F. O. Harber: I should like to describe our experience of changing over from direct to alternating current. The method we adopted was to use Scott-connected transformers and provide a single-phase supply, thus enabling us to use the existing 3-core cables; so far this system has been very satisfactory. In one or two exceptional cases of motors requiring a high starting torque, we have successfully given a 2-phase supply. With regard to Mr. Romero's statement that wireless sets can be operated more efficiently from an a.c. than from a d.c. supply, I find that the price of the a.c. eliminator is generally double that of the d.c. eliminator. I should like to ask the authors' opinion on the question whether the supply company should refund the cost of the d.c. eliminator or whether it should replace the latter by an equivalent a.c. eliminator. We have in all cases chosen the latter alternative, and the consumers have usually been quite satisfied. As regards meters, we have found that a young apprentice is able to change 15 meters per day. One of the most interesting problems I have come across was that of changing over an electrically-operated piano, which cost £260. The resistance for varying the speed worked in conjunction with a special timing device on the side of the roll which played the piano, and the price quoted by the makers for changing it over was £22 plus travelling expenses and the value of their workman's time for fitting. By installing a rectifier (which remains our own property) we were able to effect the change-over for half this price, and also cause less inconvenience to the consumer. Speaking generally, the change-over to alternating current is a consequence of the high efficiency of the static transformer, and it is interesting to speculate on the direction future developments may take if an equally efficient d.c. transformer is devised.

Mr. R. N. Pegg (*communicated*): I agree with the authors that it is impossible to lay down a standard method of change-over, as each case must be treated on its own merits. With regard to the alternative methods of using existing 3-wire distributors, the authors appear to favour the first method given on page 739, and it would seem that their distributors all have three cores of equal cross-section. In such a case, their preference is undoubtedly right, but as most 3-wire distributor systems have neutrals with a cross-section of the order of 50 per cent of that of the outers, the full-load capacity of such distributors on alternating current—even under balanced-load conditions—will be 50 per cent of the d.c. figure. This point is illustrated by Fig. 2. Single-phase distribution from delta/double-star transformers is the best arrangement where it is essential to use an existing 3-wire network. I should be glad of particulars of e.h.t. and l.t. switchgear equipments for substations as distinct from kiosks. I am sorry that no figures obtained in actual practice are given in Part 2 of the paper. Such figures would be very specialized in character, as city areas probably differ one from another more than do suburban districts. I should be glad of particulars of substation switchgear for city areas. The authors are to be congratulated on being able to pick up loads of 30 kW maximum demand on the h.t. system. I believe this practice has been adopted at Birmingham for the last few years. I should like to know the type and cost of the equipment associated with each service of this type. With regard to the change-over of wireless apparatus, the authors seem to think that the supply

undertaking has the option of accepting or rejecting the liability for the cost of this. Can any more definite information on the legal aspect of the case be given in their reply?

Mr. D. Ripley (*communicated*): I have been connected with the change-over of a number of small residential towns, and although these were all very similar to one another I found that the network conditions, the amount of consumers' apparatus, and the economics of each case, were totally different. The authors' figures of costs in relation to the maximum demand on the network should not be accepted as likely to apply to any other town, owing to the varying amount of consumers' apparatus and the fact that the quantity encountered is increasing very extensively. In the preliminary stages, when the economics of the change-over are being investigated, records are usually not available to show the number of motors under 1 b.h.p.; also a considerable amount of plant such as washing machines, coffee mills, battery-charging equipment, vacuum cleaners, and wireless apparatus, may be connected to the system. The proportion of wireless to other apparatus shown by the authors' figures does not agree with that with which I have met. At the change-over of a residential district in 1925 only about 6 motors had to be dealt with, whilst the amount of other apparatus was quite negligible.The following percentage figures for a residential town now being changed over, which formerly generated direct current, may be of interest.

Land, substation, kiosks, transformers, and equipment (2 500 kVA installed)	21
E.H.T. mains, alterations, and connections to l.t. network	21
Changing consumers' meters	19
Changing consumers' equipment	39
	100

The cost of changing the consumers' equipment (39 per cent of the whole) is subdivided as follows:—

Motors and declared equipment	65
Fans, battery chargers, washing machines, etc.	10
Medical and dental apparatus	5
Vacuum cleaners	8
Domestic wireless apparatus	12
	100

I feel that the economics of rectifier substations should be carefully investigated in the case of small towns which have been generating direct current and are now to take a bulk supply from the grid, in view of the cost of changing consumers' apparatus. Whilst all extensions to the area and probably all the surrounding part of the existing area should be given an a.c. supply, the time is rapidly coming when the initial cost of changing over will be too great, even after the allowance made by the Central Electricity Board to d.c. centres has been taken into account. In this connection the Electricity missioners have now adopted a 7-year loan period cost of changing consumers' apparatus. If everyone is satisfied that the distribution of the future will be by alternating current, why should not the loan period be made equal to the estimated life of the a.c. system, particularly seeing that once the change-over has been made the supply authority has no further liability connected with the change? The shortness of this loan period cripples the undertaking when it has not had time to secure the advantages accruing to a.c. operation. With regard to the system advocated by the authors, while the 3-phase 4-wire type seems to be essential for heavily-loaded industrial areas, for suburban and residential conversion there is a good deal to be said for the delta/double-star system. The type of system to be adopted depends entirely upon the condition of the existing network. If it is heavily overloaded, inadequate, and old, I would advocate a new 4-core network in the principal streets—supplying the existing distributors in the way the authors mention. If the existing network is sufficient and in good condition, however, I would favour the double-star single-phase system. In practice it is neither difficult nor necessarily undesirable to split up the network into phase areas; if this is done definite isolation of the requisite area is secured in the event of major faults. With a solid network comprising fused interconnections, on the other hand, a major fault may bring out a very extensive area or the wrong section (due to loading) and be difficult to trace. There is little to choose between the efficiencies of the two systems, and I entirely endorse the authors' opinion that the Scott system should be avoided. The authors assume cases for comparison where 4-core mains were partly laid down on a 3-wire system in anticipation of a change: surely if this were done the supply authority must have assured itself beforehand that the "standard" system was the right one to adopt, and this state of affairs should therefore not be compared with what would have to be done before such a combination had arisen. The authors give as their reason for discounting the single-phase system, even for suburban areas, the inferior qualities of the single-phase motor. Even if 3-phase distribution were available they surely would not alter service connections for motor supplies under 2 b.h.p. They admit the advance that has been made in the single-phase motor of small output, and I suggest that considerable advance is still possible for larger outputs. Friction-clutch pulleys are by no means universally satisfactory, and I suggest that manufacturers might consider incorporating a reliable trip-operated friction clutch in the rotor itself, which could also be utilized to effect automatic starting. The cost of repulsion-type induction motors up to 1 b.h.p. now compares favourably with that of the squirrel-cage machine, and the repulsion type is not very much more expensive up to 2 or 3 b.h.p. The authors seem to have been very courageous in regard to the scheme shown in Fig. 5, especially if the distributors were 3-core armoured cables. It would be interesting to learn the magnitude of the 3-phase load referred to, the inductive drop entailed by the out-of-balance currents in the separated distributors in comparison with the resistance drop, and whether the cables were tape- or wire-armoured. For 3-wire single-core unarmoured conductors with the outers spaced 8 in. apart, I have found the inductive

drop at 0·8 power factor to be very appreciable. The last paragraph of the paper indicates that the authors have valuable information to give concerning the inductive losses in single-core armoured cables of various sizes at different loadings, and I hope that they will publish this in their reply. Such information would be very helpful, as the loadings and inductive drops in interconnected networks are usually founded on guesswork backed by experience. In this connection I found by actual test, in the case of a housing estate supplied off single-core wire-armoured cable of 0·0225-sq. in. cross-section, that up to 25 amperes the total drop was almost the same as the resistance drop. On plotting the a.c. drop against the load I found no indication of inductive drop up to this loading.

(The authors' reply to this discussion will be found on page 766.)

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 21ST MARCH, 1932.

Mr. R. H. Rawll: The authors indicate in Table 1 the numerous types of systems of supply for low-tension distribution existing at present in this country, and rightly stress the importance of the standardization of low-tension systems. There is, however, another factor of even greater importance, and that is the need for the standardization of low-tension voltage at the recommended figure of 230/400 volts. The confusion caused by the use of different voltages is even greater than that due to different systems of supply, and a decidedly retrograde step is being taken by numerous undertakings in perpetuating a non-standard voltage when changing over from direct to alternating current. Such a step should be prohibited by the proper authority. It is somewhat difficult to follow the authors' reasoning regarding the contribution they suggest the Central Electricity Board might make when a d.c. generating plant is shut down and the opportunity is taken—on obtaining a bulk supply from the "grid"—to change over the l.t. network from direct to alternating current. I am of the opinion that this suggestion is based on a misconception of the Central Electricity Board's powers and functions in such a set of circumstances as is outlined in the paper. The method shown in Fig. 4 of feeding existing 3-wire distribution mains from a 3-phase 4-wire supply on a housing estate is, of course, a practicable one, providing a reasonable balance can be obtained. On most housing estates the lighting load is predominant, and such a method of distribution will soon give trouble if the heating load develops. The bunching of 3-core feeders to form one 3-phase feeder may be all very well as a temporary expedient, but taking future developments into account it is quite possible that the total cost of the network alterations ultimately found to be necessary on account of the growth of load will in many cases render such a practice unprofitable. The great disadvantage of the delta/double-star method of transformer connection is the difficulties and limitations met with in regard to interlinking with other areas of the l.t. network fed from a different source. In Table 3 the authors omit to mention that the great disadvantage of the single-phase system of supply is that all the motors used on system (*a*) must be of the single-phase type. This fact obviously limits the size of the units in question, besides curtailing the numbers installed by consumers, on account of their high cost and inferior performance compared with 3-phase machines. From Table 4 it appears that the capital cost of installing a 4-core cable will be roughly 10 per cent more than that for a 3-core cable. The increased interest charges on this extra amount are, however, very small compared with the saving due to the 33 per cent decrease in losses which would be obtained, and for this reason where new mains have to be laid it is obviously a paying proposition to install 4-core cable. The authors state that if the displaced converting plant is sold for use in another d.c. system, the sum obtained from the sale might reasonably be credited to the cost of the change-over and would greatly reduce the total cost. That the total cost would be very little reduced, however, can be easily shown if the case of two 500-kW rotary convertors is considered. A substation with two such machines installed could reasonably be expected to have a maximum demand of 625 kW. According to Fig. 7, the cost of changing over such a network is £18 per kW of maximum demand, representing about £11 100 in the case under consideration. Although the cost of new rotary convertors to-day is about £3 per kW, their second-hand value is only about 10s. per kW. Two 500-kW sets would therefore be sold for about £500, which if put to the credit of the total cost of the change-over only reduces this item by about 4·5 per cent. The amount that would be realized from the sale of rectifiers is even less. It is not clear what is meant by the subdivision numbered "4" in Fig. 8, which represents the comparative costs on direct and alternating current for maintenance and repairs of consumers' apparatus. This item will vary in size according to whether the supply undertaking carries out all such repairs and maintenance, a very unlikely supposition considering that the local electrical contractors usually do the bulk of this work, and therefore the figure given in Fig. 8 for this item is valueless. I agree with the authors that a.c. meters are more sensitive than d.c. meters. Although it is true that since the former registers kWh and the latter ampere-hours, the a.c. meter is the more equitable to both the supply authority and the consumer, yet in changing over a consumer from direct to alternating current it is difficult to convince him that the slight increase in registered consumption which usually takes place can be legitimately accounted for. I fail to understand why in approximately 5 years the total cost of changing over should be recovered from development charges alone, assuming an annual increase of load of 15 per cent. It seems to me that the cost of changing over bears no relationship to the revenue derived from the increase of load which is to be expected. As regards the statement that some supply authorities are introducing preferential terms for good power factor, it will usually be found that this only applies to large consumers taking an

e.h.t. supply. I do not think it is correct to say that until recently the a.c. motor was at a disadvantage compared with the d.c. motor, and I should be interested to have the authors' reasons for this statement. Although it is an advantage if all new power consumers can be prevailed upon to install wiring for a 3-phase supply in anticipation of an intended change-over, there are very few cases where this can be effected at the consumer's expense. It would be interesting to know whether the author's figure (Fig. 14) for the cost of changing over consumers' apparatus in industrial areas includes the rewiring costs for 3-phase supplies; these charges form a large proportion of the costs of a change-over in industrial areas as distinct from residential areas, where consumers' apparatus is mainly single-phase and consequently very few wiring alterations are necessary. Various undertakings have interpreted differently their liability in connection with the changing of consumers' apparatus, particularly domestic wireless apparatus, which, as shown in Figs. 7 and 19, accounts for a large and increasing proportion of the cost in residential areas at the present time. Although undertakings may get from wireless apparatus very little return in revenue compared with the conversion costs which are necessary on changing over, it is better to take the long view and make the domestic consumer satisfied, since it is he who has to be "cultivated" for load-building purposes. Consumers with a sense of grievance developed at times of change-over may easily become permanently prejudiced against the further use of electricity in their homes for water-heating, cooking, etc. With regard to the change-over from direct to alternating current of l.t. networks concurrently with a change of frequency of the e.h.t. supply; although it is true that, with the contribution which might be expected from the Central Electricity Board in such circumstances, the total cost would be less than if the change of frequency were carried out first and the l.t. change-over later, the main factor is whether the frequency change-over can be held up long enough to enable the change-over of the rotary-convertor or rectifier load from direct to alternating current to be carried out. It will be appreciated that whereas a 200-kVA 25-cycle load in a factory can be changed over to 50 cycles per sec. in a week-end, a similar d.c. load on a rectifier feeding a low-tension distribution network might take several weeks to change over to alternating current. It is essential to have everything ready, particularly consumers' apparatus, before a change-over is begun. Finally, I would urge that the standardization of the 230/400-volt 3-phase 4-wire distribution system should be tackled as a national rather than as a local problem.

Prof. W. Cramp (*communicated*): In many urban areas the engineer organizing the change-over will not be in so fortunate a position as was the case in Birmingham. I could quote instances in which a d.c. 3-wire network has been laid in the form of separate cables side by side and run solid in metal troughs. If such cables are not lead-covered, it is unlikely that eddy currents in the metal trough will seriously interfere when an a.c. supply is adopted, but everything depends upon the spacing and each case would have to be examined separately. Again, in some instances existing d.c. networks consist of single-core armoured cable, which could not be changed over in any case. I should be glad to know whether the authors have had any experience of such difficulties, and, if so, what steps they took to overcome them. Also, in many areas already, consumers find it necessary for their special purposes to transform from alternating to direct current, and such consumers on an existing d.c. system would expect to be provided with converting plant. What do the authors propose in these circumstances? The costs of the change-over are so alarming that it would, I think, often be unjustified were it not for the low figure of maintenance which the authors quote. This amounts to £1 10s. 0d. on an expenditure of £20, i.e. 7½ per cent. It is therefore exceedingly important that this figure should be substantiated and a more definite statement made as to what it includes. The capital costs of a rectifier substation are shown in Fig. 9 to be higher than those of an automatic rotary substation. Are the figures based upon rectifiers of the glass-bulb type, and would it be correct to state that above 500 kW the price would be lower for the steel-cased type?

[The authors' reply to this discussion will be found on page 766.]

North-Western Centre, at Manchester, 22nd March, 1932.

Mr. J. B. Lees: I would go further than the authors, and suggest that single-phase distribution concurrent with a change-over should not be considered. It is surely economically sound to approach the "standard" system, which is likely to constitute finality, in one step rather than in a number of "easy" stages. It is my experience that motor loads are encountered even in suburban areas. The 230-volt single-phase motors which would have to be supplied would necessarily remain when the single-phase system was changed to the "standard" 4-wire system, and they would undoubtedly give rise to fluctuating-voltage trouble at times when this would be noticeable. On page 738 the authors express the opinion that if a d.c. generating authority decided to change over, concurrent with taking a supply from the Central Board, the whole of the estimated costs of transformers and convertors might still be obtained from the Board and used towards the cost of changing over. I should be glad to know what authority they have for making such a statement. The comparison of costs in Fig. 7 shows what would appear to be an excessive amount for consumers' apparatus. It is my experience that considerable economies can be effected in this direction without irritating the consumer. As regards heating apparatus, for example, my experience has shown that many 210-volt elements in water heaters, fires, irons, etc., will operate quite satisfactorily on 230 volts without their life being seriously affected. I suggest that heating apparatus which is in good condition should be left, and the under-

taking concerned guarantee to exchange elements which break down within, say, 12 months, the period for which they are normally guaranteed by manufacturers. A consumer with a *bona-fide* charging apparatus has, of course, a case for exchange. In those cases where a consumer has interrupted his lighting or power circuit to use either load for charging purposes, I suggest that no apparatus should be supplied. My experience has been that at least 50 per cent of the domestic consumers changed-over who charged their own batteries, did so by interrupting a circuit, probably as a result of a word from an enterprising contractor. The position with regard to d.c. mains-driven wireless apparatus deserves firm and concerted action. Any form of d.c. mains apparatus is dangerous to life, and I consider that its use should constitute a breach of supply authorities' regulations. As a load it is of no use to the supply authority, and it is of no value in helping to make consumers electrically-minded. Further, if an a.c. supply had been available at the outset, the consumer would have had to bear the expense of the additional apparatus, i.e. the transformer and rectifier. It appears to me, therefore, that he should bear this expense when changed over. In conclusion, I should like to know whether the two isolated cross-shaded areas on the left-hand side of Fig. 17 are saturated manufacturing areas. If not, why were they not changed over together with the surrounding area?

Mr. J. L. Carr: Unfortunately the authors' system does not seem to have been involved in a change of voltage as well as of type of supply. There are some points in the paper to which exception might be taken. I notice, for example, that in the Summary the authors claim that change-over from direct to alternating current can be carried out in a satisfactory and advantageous manner from an engineering " as well as " from an economic standpoint. The attempt to divorce economics from engineering is fundamentally unsound. A piece of work which is technically good but economically unsound is bad engineering. Further, a technically bad job can never be economically sound. An engineer's duty is to make the best use of the materials at his disposal, and those materials include financial resources. Engineering is therefore bound up with economic considerations; and the sole justification for undertaking an extensive change-over of a d.c. network is the economic argument. It is very much cheaper to distribute electricity by an a.c. 4-wire system than by direct current. On the other hand, the d.c. system has undoubted technical advantages, particularly as regards voltage regulation. The regulation of an a.c. system is inherently poor, and unless automatic regulating devices are used the results cannot be so good as those obtained with the d.c. system. I support the claim for the use of standard systems. Although the authors refer to the standard system recommended by Messrs. Beard and Haldane,* in point of fact they do not adhere to the standard distribution network. The system they advocate is similar to the old d.c. feeder network system. In the standard system recommended by Beard and Haldane the low-voltage feeder was dispensed with and a distribution network was used; that is to say, the low-voltage d.c. feeder with its high first cost and large losses was replaced by high-voltage feeders and transformers placed at suitable feeding-points for a small distribution network. By using feeder networks in several places, as the authors suggest, one loses a great deal of the advantage of a.c. distribution. The distribution network system is a logical development in electricity supply, and it undoubtedly possesses substantial economic advantages. Another point to which exception might be taken is the use of colours. Although the colours for a 3-phase 4-wire distribution system are not definitely specified in British Standard Specifications, in at least one such Specification the phases are coloured red, white or yellow, and blue. In the I.E.E. Wiring Regulations the phase colours for internal wiring are red, white, and green, and the neutral is coloured black or blue. It seems to me that some standardization of colouring is necessary for stations, transmission and distribution systems, and interior wiring. In connection with the use of 3-core distributors, when a change-over was first considered in this district it was decided that as much use as possible should be made of the existing 3-core distributors. The system finally adopted was very similar to that suggested by the authors. In some outlying districts motors had to be dealt with; as single-phase motors of more than 1 or 2 h.p. are expensive and possess certain undesirable characteristics, in residential districts I suggested the use of an inverted balancing transformer in order to make the 3-phase energy available from a 2-phase-and-neutral supply. We have used quite a number of these devices, usually with a little additional compounding in the derived phase in order to provide for better voltage at the motors, with some measure of success. The result is that by providing a squirrel-cage 3-phase machine the cost of conversion is cheapened, and at a later date when mains extensions become necessary a 4-wire service can be taken in without further difficulty. With regard to the replacement of a.c. motors at the Ford works at Michigan, U.S.A., mentioned on page 748, although the authors use this matter as a justification for supply undertakings carrying out the change-over from direct to alternating current, the conditions are not comparable. The former is a case of a manufacturing concern changing over of its own accord in order to obtain more efficient running and lower production costs, whereas an electricity supply undertaking is concerned merely with reducing the cost of distribution. This point should be borne in mind, however, when approaching the owners of a big works which it is considered desirable to change over, because it may induce the works manager to consider contributing towards the expense. This is particularly the case if the works are sufficiently large to justify a high-voltage supply and consequently a lower tariff. In such cases it is only reasonable to assume that the cost of the change-over should be borne by the owners of the works.

Mr. G. G. L. Preece: The authors' case in favour of changing over is all the stronger because Birmingham was one of the big towns that opposed the pressure put upon them by the Electricity Commissioners in connection with both the change-over to alternating current and the frequency change. Is it, however, certain that

* *Journal I.E.E.*, 1927, vol. 65, p. 97.

the authors are altogether right? Many chief engineers of supply authorities consider that the expenditure involved in changing over is so large that the resultant gain in efficiency does not give a fair return on the money spent. All supply authorities are, however, agreed that in outer areas and on new work, a.c. supplies should be employed. With regard to substation equipment, there is no doubt that with a.c. apparatus one obtains a much greater kW capacity for a given sum spent than with converting plant. However, the interesting experiments recently carried out in Switzerland in regard to the grid control of mercury-arc rectifiers show high-tension d.c. transmission to be a practical proposition. Had these ideas been evolved a few years earlier I doubt whether large-scale a.c. transmission would have developed so rapidly. The question of voltage regulation, mentioned by Mr. Carr, constitutes a real difficulty in regard to a.c. distribution. A cheap and efficient automatic voltage regulator for use on the l.t. side of transformers is badly needed at the present moment. The regulators at present available are so expensive in relation to the cost of the transformer that they are not being widely adopted.

Mr. W. E. Swale: The authors rightly stress the desirability of changing over only to the standard voltages of 400 and 230 volts. Yet one hears of cases where a lighting voltage of 200 volts has been deliberately retained on the a.c. system in order to save the cost of replacing electric lamps and fires. Part 2 of the paper states the advantages of change-over mainly from the point of view of the undertaking. The arguments on the side of the user may be summarized as follows:—

(*a*) The maintenance charges of a.c. motors and control gear are less than those of the corresponding d.c. plant.

(*b*) Alternating current is more adaptable to all classes of electric furnaces and heaters than direct current. Certain types of high-temperature furnaces, electrode water-heaters, and a large variety of electro-medical appliances, cannot be made for use on d.c. supplies.

(*c*) Engineering and metal-working firms find alternating current a necessity for the many resistance welding methods now employed.

(*d*) In city areas the use of neon signs has brought the advantages of alternating current to the notice of the user.

These claims for a.c. distribution, in addition to those advanced by the authors, form an overwhelming case in favour of changing over. The main question at present facing supply authorities is: Shall we complete the industrial change-over in 2 or 3 years, or shall we spread the expenditure over about 10 years? I suggest that in the case of large and old concerns the right policy is to proceed gradually, and to allow the factors of time and obsolescence to effect a considerable amount of gradual weeding out. Unfortunately there are certain types of apparatus—notably lifts, dental machinery, hydro-extractors in laundries, etc.—where the cost of making the change-over is out of all proportion to the revenue derived from the energy consumed. In such cases do the authors not think it advisable to leave a limited d.c. supply on the premises, whilst changing over all the straightforward apparatus? Turning to the suggestion on page 747 that "the consumer . . . might even be persuaded to pay part of the cost of changing over," I think that if the case is put to him properly the large power user will often be pleased to pay a substantial contribution towards the cost of the change-over, which gives him the following advantages: first, a new set of motors of appreciably greater second-hand value than his d.c. motors; secondly, new wiring which will last him for 20 to 30 years; and finally, a unique opportunity of reorganizing his drives and equipping himself afresh to meet the intense competition of to-day. Finally, as regards power factor, the time will surely come when all medium and large power users will be penalized or benefited by low or high power factor respectively. Has the suggestion made on page 746 been adopted by the authors? If so, I presume that they put in static condensers.

Mr. O. Howarth: I should like to take up the question of power factor where Mr. Swales left off. Although the authors suggest that correction should be dealt with from the high-tension side by installing power-factor-correction plant at certain selected substations, it seems to me that merely to correct the power factor on the high-tension system will be of little benefit to the undertaking. The principal gain will be to the station and the high-tension transmission system. The best way, if it can be done cheaply, is to correct the power factor at the load. It certainly is a decided advantage to correct the power factor on the low-tension side of the step-down transformers and thus reduce the transformer capacity. As to the question of wireless sets and battery chargers, I think the reasonable course to take is to compensate the owners of such apparatus for the loss they incur by being deprived of the use of the particular appliance. This compensation will help to pay the cost of new apparatus suitable for use on the a.c. system. After all, if an a.c. supply had been available in the first instance the consumer would not have been able to supply himself with a battery charger or wireless eliminator for the cost which the d.c. supply made possible. I should like to ask whether the authors do much in the way of bringing installations into line with modern requirements when they change them over. On many old d.c. systems metal tumbler switches which do not conform to present requirements are fixed over stone floors. Do the authors persuade the owners to change such switches? I would point out that such practices as these are more dangerous on a 230-volt a.c. than on a 230-volt d.c. system. One considerable advantage of a.c. over d.c. supplies in works or houses is that short-circuits are much less severe in the case of the former, and the damage caused thereby is not so great. The earthing of electrical appliances is very important when alternating current is used. It is illogical for a supply undertaking to insist on a consumer having insulated switches and lampholders over a stone floor if the undertaking is willing to sell a kettle which will be used in the same room without any provision for earthing.

Mr. G. L. Porter: Have the authors been quite fair to the 3-wire single-phase system? Domestic apparatus is essentially single-phase, and as long as the phase-to-neutral voltage is standardized complete standardization is attained. Should a demand for power supply develop unexpectedly in a residential area and the size

of motor be such that the single-phase supply is unsuitable, it is certain that a 3-phase supply could not be given satisfactorily from a 3-phase 4-wire network laid down in the absence of such a power load. Such a supply would therefore, in any case, have to receive special treatment. The change-over to a 3-phase 4-wire system is also not so easy as the authors suggest. With regard to their mention of existing 4-core cable installed in anticipation of the change-over, as most extensions are made at the tail ends of the network such portions of 4-core cable are of little assistance. Moreover, the use of existing 3-core cables as main distributors is not such a simple matter as might be inferred from their remarks. Fig. 4 shows the ideal case of three such cables of equal cross-sections. In practice the available cables are much more likely to consist of two along opposite sides of a main road, and frequently the cross-sections are not the same. It will further be seen in Fig. 4 that the resultant of the currents in the three cores of any one of these cables is not zero; if the cables are not metal-sheathed there will in consequence be a considerable reactance voltage-drop. As these voltages have a phase difference of 120°, in different cables the currents in the two cores forming one phase will not be in phase with each other, and there will also be circulating currents in the neutral conductors. If the cables are lead-sheathed these voltages will be reduced as a result of the similar circulating current in the lead sheaths, but they may still be considerable. While the reversal of the neutral current in the vector diagrams makes it easier to identify that current, some justification of the practice should have been given in the paper. The advantages of changing over to an a.c. supply should be amplified by the authors. One important advantage is the elimination of substation attendance cost, or, alternatively, the reduction in cost of automatic or remote control; further, on an a.c. system local means of voltage regulation or load balancing can be easily adopted. Another advantage is the great reduction in cost of mains maintenance where vulcanized bitumen cables are in use. Lastly, an a.c. mains supply can be safely used for " all-mains " wireless sets and for bells, etc., while cookers and apparatus in damp situations, such as sculleries and wash-houses, are much less liable to breakdown when operated by alternating current.

Mr. J. Penrose: I shall deal first with the important question of voltage regulation. When the system is operating at full load, the voltage at the generating-station busbars being maintained constant, the voltage-drop from generator busbars to consumers' terminals is of the order of 12 per cent. Owing to diversity this full value will not be reached, the actual figure being 7·5 to 10 per cent. This figure may be exceeded due to local conditions, e.g. heavily-loaded distributors, especially when there are large out-of-balance currents. The effect of bad voltage regulation on consumers' apparatus is considerable and very undesirable. Dealing with Part 2 of the paper, change-overs of industrial areas are the most difficult ones to undertake. In such areas the authority has the heaviest obligation, whilst the consumer reaps the greatest advantage. The existing plant is generally out of date. In Manchester every effort has been made during the past few years to prevent additional industrial loads being connected to the d.c. system; a.c. nuclei have been provided at many points to absorb these new loads. I suggest that intensive propaganda should be carried out to acquaint consumers with the advantages of modern plant, in order to induce them to shoulder some of the burdens which fall on the supply authority. In Manchester considerable lengths of vulcanized bitumen cables have been, and are still being, replaced. The new cables are of the 4-core type, and in many cases 2 × 0·25-sq. in. 4-core cables have been laid instead of 1 × 0·5-sq. in. cables. Suitable balancing of the load will prevent difficulties occurring when a general change-over takes place. The connection of the large power consumer to the high-tension system is to be recommended. The power factor is generally very low for industrial loads—sometimes as low as 0·65—and in my opinion special power-factor tariffs should be given even to small power users in order to induce them to effect an improvement in the power factor of their loads. I should be glad of the authors' opinion on this point. The figures of cost given in the paper are probably not representative. To relieve the d.c. conditions, a portion of an industrial area in Manchester was changed over a short time ago, and the cost per kW demand for conversion of apparatus was in excess of those in the residential districts. The authors' figure for conversion of apparatus seems to be too low, and this is probably due to the relief on account of change of frequency. There is a largely increased demand for electricity in city areas. In addition to the anticipated improvement in trade resulting from the re-occupation of premises now vacant, and augmented by new demands which have arisen out of recent developments, the following factors have to be considered. (*a*) Improved standard of illumination. (*b*) Electric lifts, which are rapidly replacing hydraulic lifts, but are very expensive to convert. (*c*) Neon signs, for which there is a rapidly increasing demand. (*d*) Flood lighting: I anticipate a great development in this form of exterior illumination. (*e*) Electric cooking. The anticipated increased demand will result in overloading of existing d.c. feeders, which will have to be augmented unless a change-over is carried out. I should like to have seen in the paper a balance sheet showing the annual development charges for a.c. as against d.c. supplies, including the value of the kW demand on generating-station busbars, and the annual kW output from the generators. The savings in kW demand and kWh output in the case of alternating current are quite important, especially in view of the operation of the national " grid " system.

Mr. G. H. Sammons: I should like a little explanation of Fig. 18, the caption of which is not quite clear. Is it a running total, or is it the number of consumers changed over per year, which is plotted? If the latter, next year about 30 000 consumers will be changed over. I should like to say a word about single-phase systems. In a district where each house takes up 100 yards of road frontage one cannot distribute economically by means of low-tension current, and in such cases it is necessary to resort to single-phase distribution by 2 000-volt feeders. I do not think we shall ever get a standard low-tension distribution system in this country. Single-

phase supplies will always be adopted in certain districts. On page 747 the authors recommend that consumers with maximum demands of 30 kW or over should be supplied direct from e.h.t. mains. Can this suggestion be carried out? There are thousands of shops and even houses in England with more than 30 kW of load, and to install an e.h.t. supply in all such cases seems to be going rather too far. Although the authors refer to the lack of standardization and state that apparatus bought in one town will be useless in another, they also state that, when they change over, 220-volt lamps are connected to the 230-volt a.c. supply. I myself have used on a 230-volt system for 6 months without trouble 2-kW fires and a 6-kW cooker bought for a 210-volt supply. The authors' figures (page 744) of 10·8 faults per 100 miles of distribution main per annum on d.c. networks and only 0·99 on a.c. networks give a very unfair comparison between the two systems. I have no doubt that much of this 100 miles of d.c. mains consists of vulcanized bitumen cables, and to compare old types of d.c. cables with modern paper-insulated cable is not quite fair. Similar modern cables properly laid will last just as long with a d.c. as with an a.c. system. The majority of d.c. cables in the past have been laid in congested areas, whereas the majority of a.c. cables have been laid in quieter areas, or in connection with housing schemes where they are not so liable to be damaged by other authorities, by vibration, or by subsidence. The ratio of 10·8 to 0·99 does not represent the true comparative efficiencies of the two systems.

Mr. A. E. Jepson: I should like to refer to the question of voltage regulation on a.c. systems. Out of nearly 250 tests made in Manchester and neighbouring towns, over 50 per cent showed the a.c. voltage to be at least 2 or 3 per cent above the allowable voltage increase of 4 per cent. These tests were carried out because it was found that lamps were not lasting for their normal life. There is a good deal to be said for Mr. Swales's suggestion about the advisability of waiting for obsolescence. Mr. Sammons stated that in his own particular case, when changing over from 210 to 230 volts, it was not considered necessary to change the apparatus. This is hardly fair to the consumer, particularly as many a.c. supplies are actually given at 240 volts instead of the declared 230 volts, because allowance is being made for future loads. If the voltage on the apparatus is increased so much, the watts will increase out of proportion, and the temperature of hot plates will increase to such a value as to reduce their life considerably. It is unfair to suggest that because in one particular case the apparatus has lasted for 6 months without giving any trouble, one is justified in connecting other consumers' apparatus to such a high voltage without giving them any compensation. While it would be a pity to scrap apparatus which might have 6 to 12 months' life at the higher voltage, it would do the supply authority no good to be unfair to the consumer. I cannot see that, in changing over, any discrimination should be made between a wireless set and a vacuum cleaner. Various speakers have suggested that the responsibility for changing over wireless sets should be with the consumer, despite the fact that the cost of changing over vacuum cleaners is met by the supply authority. A wireless set actually consumes in the course of 12 months rather more electricity than a vacuum cleaner.

Mr. C. L. E. Stewart: On page 738 the authors state that the Central Electricity Board bear the cost of converting d.c. supplies to a.c. supplies; do the Board bear the cost of making the supply authority's system suitable for receiving a supply from the "grid"? While they certainly do pay for changes of frequency, under a special clause in the 1926 Act, I have always understood that they go no further. I would emphasize that when a supply authority propose to change over from direct to alternating current they have to advertise the fact, and to state in the advertisement both the rights of the consumer and the liabilities of the supply authority. The consumer therefore knows exactly what he can demand. I should like to ask whether the authors have included in their estimates the cost of transferring consumers' services to new 4-core cables when these are laid for the purpose of change-over. In certain cases, especially small residential areas, it is in my opinion quite sound practice, and certainly the cheapest way, to transfer whole streets at a time by leaving the existing 3-core d.c. mains in and connecting them to two phases and the neutral.

Mr. A. H. Fay: I should like to ask what has been the authors' practice regarding the utilization of existing 3-core feeders on a "standard" a.c. system. What do they find the effect of unbalanced loading to be in relation to the voltage-drop? I should welcome the authors' opinion as to the limits in size of single-phase motors. The generally-accepted economic size seems to be 2 h.p., despite the fact that 2-h.p. single-phase motors cost exactly twice as much as the 3-phase type. Have the authors met with many cases—directly attributed to change of system—of increased revenue since the change-over? In reference to the "Summary to Part 1" (page 746), I suggest that consumers could have additional d.c. supplies if they would indemnify the authorities against the cost of the replacements which the change-over will necessitate. Turning to the suggestion on page 747 that the transfer of the load to alternating current would permit of reductions in the length of d.c. feeders, which would thus be able to deal with increased demand on that portion of the d.c. network nearer the substations; my point is—why deal with any increased d.c. demand unless the consumer indemnifies the supply authority? On page 750 the authors state: "No new d.c. plant should be installed, and as the existing plant requires replacement the a.c. system should be extended and the d.c. system reduced." This view does not seem to coincide with that expressed on page 747. The large figure of 240 consumers changed over in a day in Birmingham is explained by the fact that the voltage of 230 volts remained unchanged, and therefore no apparatus other than meters and motors had to be changed over. How many meter fixers were employed in Birmingham to change 240 meters per day? In regard to page 752, par. 12, I do not see the wisdom of obtaining from the consumer an acknowledgment that his change-over has been satisfactory. This seems to be a needless proceeding, because there are many people who will never admit that they are satisfied.

Mr. W. J. Forster (*communicated*): With regard to

the authors' three alternative ways of changing over from direct to alternating current (page 739), I regard all change-overs to single-phase as temporary measures, for use until the laying of 4-core cables and the complete change-over to a 3-phase 4-wire supply can be justified. I am glad to note in this connection, however, that the authors prefer the delta/double-star connection for single-phase supply, as this enables a 3-phase supply to be given from the substation for power consumers. I note that the authors do not mention the use of static balancers or auto-transformers on 3-phase 3-wire mains. I recently had to change over a consumer who used both power and lighting, and was supplied by a rather long 3-core cable. As 3-phase supply was required for power purposes, and as the lighting load was quite small, an auto-transformer was installed to give 230 volts for this purpose. For larger installations a 3-phase static balancer could be installed so as to provide an artificial neutral point. In connection with the procedure of carrying out change-overs, the lantern slide exhibited by the authors showed that the inventory was made after the loan sanction had been obtained. This appears to be illogical, as it would be rather difficult to prepare an estimate of the cost of a change-over without a knowledge of all the consumers' apparatus. I agree, however, that it is necessary to make a second inventory just before the change-over takes place, as consumers may have installed additional apparatus since the first inventory was prepared. It would be helpful if the authors could give some idea of the cost of sites for substations, which I find varies considerably from one town to another.

Mr. S. R. Mellonie (*communicated*): Figs. 14, 15, and 16 are interesting as emphasizing the small proportion expended on transformers and switchgear, and I should like to know the type of switchgear the authors have included for both the high- and the low-tension sides of the transformer; also the amount of spare capacity included in the figure for the transformers. The cost of the low-tension switchgear (if any) depends to a large extent on the maximum capacity of the installed transformers, and perhaps the authors would state the maximum size of substation to which these costs apply. It is well known that the cost of low-tension switchgear increases rapidly with the rupturing capacity, which in turn is determined largely by the size of the transformer bank installed. The suggestion is put forward on page 746 that the power-factor correction equipment should be installed on the high-tension side. The efficacy of this method is doubtful, however, having regard to the fact that 80 per cent of the drop on the average system is due to the reactance of the transformer and the resistance of the low-tension cables, which under these circumstances would still carry the wattless component of the load. The ideal position for the power-factor-correction apparatus is as near the consuming plant as possible.

Mr. B. S. Orme (*communicated*): I cannot agree that the consumer should contribute towards the cost of replacements rendered necessary by a change-over. It must be remembered that much of the domestic and industrial electrical apparatus already installed in consumers' premises would not have been purchased but for the commercial enterprise and advice of the supply undertaking. The change-over from direct current to low-tension alternating current is being carried out primarily in order to simplify the operation of the supply undertakings, the benefit to manufacturer and consumer being of an entirely secondary nature. The consumer is faced with the alternatives of agreeing to the change-over without reimbursement or having the supply to his premises discontinued. This treatment is unduly harsh; but as the supply authorities have the whip hand the consumer has no option but to submit to it. With regard to power-factor correction, it appears to be the business of the commercial engineer of the undertaking to advise consumers what equipment to install for the purpose of eliminating wattless kVA. I should be glad if the authors could state at what horse-power it is more economical to install a synchronous motor with its attendant starting-gear than to put in an induction motor.

Mr. H. Shackleton (*communicated*): The authors appear to have been in a comparatively happy position with regard to change-over, for apparently in their case no change in effective voltage was involved. The lighting, heating, and cooking apparatus connected to the system therefore required no alteration. This fact perhaps renders the costs of changing over consumers' apparatus (Fig. 14) less indefinite than they would be in general. I regret that the above costs are in the first place estimated costs, and, secondly, that they are based on maximum demand. Even if the latter is known prior to change-over, the amount of connected load required to produce this demand may vary between very wide limits, depending on the type of connected load, and how it is used. In addition, certain motors may have been out of commission for some time. Their effect on the maximum demand will therefore be nil. On the other hand, these motors have to be changed over. Whether or not the cost is proportional to the maximum demand, the amount of equipment to be converted must affect the cost of change-over. I suggest, therefore, that the most useful and most straightforward way of stating the above costs is per kW converted, the load to be converted being easily obtained from the inventories. In presenting the paper Mr. Blades mentioned that a.c. distribution in a city area suffered from the disadvantage that no stand-by battery was available. In the past, the cost of a stand-by battery of sufficient capacity to provide an emergency supply was comparatively small. In certain areas, however, the load has developed so rapidly that the stand-by battery is no longer capable of giving an adequate emergency supply, and numerous complications may arise when the question of increasing the capacity of the battery is considered. It would appear unfair, therefore, to state without qualification that d.c. distribution is superior to a.c. distribution in this respect.

Mr. A. V. Sowman (*communicated*): One or two supply authorities in Lancashire have experienced considerable difficulty in changing over certain complete areas from direct to alternating current. The following cases were particularly difficult. (*a*) A 2-b.h.p. variable-speed silent d.c. motor was installed in a church, driving a church organ in conjunction with an automatically-

operated rheostat for varying the speed of the motor from practically nil up to full speed. It was not possible to replace this d.c. motor by an a.c. commutator motor, as commutator motors are noisy, and the existing bellows were quite unsuitable for varying the brush position of a commutator motor. A motor-generator was therefore supplied to the church, in order that the d.c. supply might be continued. (*b*) In the case of a foundry employing a large number of d.c. magnets for lifting purposes, and having a number of d.c. electric hoists and cranes, it was found advantageous to install a motor-generator or small rotary convertor to enable the d.c. supply to be continued. (*c*) A similar case was met with in connection with a newspaper printing firm using a number of automatically-controlled rotary printing equipments, having a speed variation from 1 or 2 r.p.m. up to 750 r.p.m. In this case the d.c. supply had to be continued, owing to the tremendous cost of changing over to suitable a.c. equipment. I should be glad to know whether the authors have met with the same difficulties, and, if so, how they have overcome them. If a motor-generator set, rotary convertor, or rectifier, is installed on the consumers' premises, who is held responsible for the running of this plant? Is metering performed on the input or the output side of the converting plant?

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, BIRMINGHAM, AND MANCHESTER.

Messrs. H. Blades and **A. C. MacQueen** (*in reply*): We are gratified to find that the criticisms of our paper show a very large measure of agreement with our principal proposals. With one exception all the speakers seem

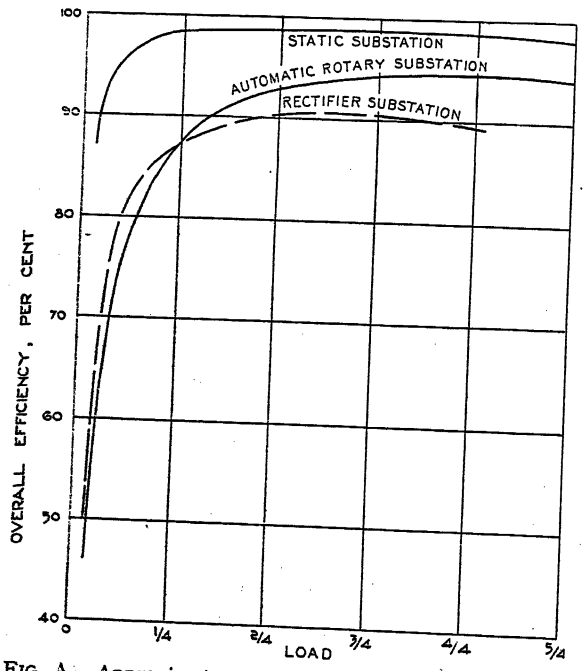


FIG. A.—Approximate comparative overall efficiency of static, rectifier, and automatic rotary substations for suburban areas.

to agree that an a.c. system of distribution is better and more efficient than a d.c. system, and there appears to be general agreement as to the advantages to be obtained from changing over. There is a difference of opinion, however, as to the best type of system to adopt in suburban areas and as to the rate of change-over in city areas.

Comparison of D.C. and A.C. Systems.

Mr. Mordey agrees that high efficiency is as important in distribution as in generation, but he is not convinced that by a change-over to alternating current a higher distribution efficiency can be obtained. He cites a case where investigation showed that a small town was more efficiently supplied by direct current than it could be by alternating current. We understand that in this particular case a d.c. generating station was situated in the centre of the town. No mention is made of the voltage of generation or of a high-tension transmission system, and we assume that the supply was given by l.t. feeders and distributors only. In our opinion such a system could only be used economically with a maximum radius of supply from the generating station of about 1 mile, and even with this limited radius of supply

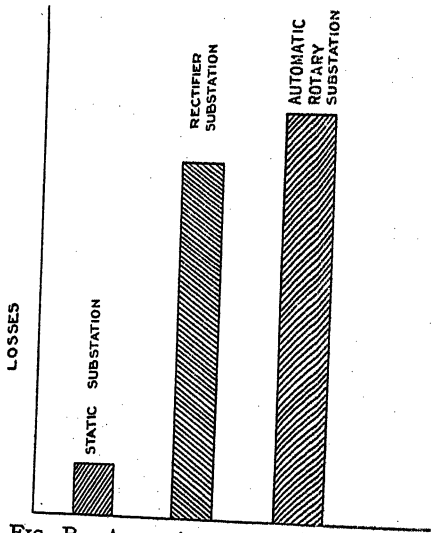


FIG. B.—Approximate comparison of no-load losses on static, rectifier, and automatic rotary substations for suburban areas.

the distribution network would require to be lightly loaded. A system of this type would, of course, be out of the question except for villages or very small towns, and even in such cases the development of load would be limited to such an extent that a.c. generation and h.t. transmission would probably have to be adopted ultimately. The investigation carried out by Mr. Mordey is therefore only applicable to a particular case and really bears no relation to the subject of the paper. Mr. Mordey also suggests that the efficiency curves in Fig. 12 would be of more value if they were continued almost down to zero. This has been done in Fig. A, and the comparative no-load losses to correspond to

these curves are shown in Fig. B. An examination of Figs. A and B shows that the lighter the load the more pronounced is the advantage of a.c. supply. Under modern conditions where invariably an e.h.t. transmission system and transforming or converting centres are employed, there is no doubt that a.c. distribution is more efficient than d.c. distribution.

Choice of a System in Suburban Areas.

Mr. Romero and Mr. Porter are in favour of adopting a permanent single-phase system where an existing 3-wire network is being changed-over to alternating current. Messrs. Steel, Pegg, and Ripley, favour a temporary single-phase supply with a second change-over to the " standard " system at a later date, and Messrs. Lees, Carr, Rawll, and Preece, support a change-over to the " standard " system in one step. The two last-mentioned alternatives are recommended in the paper. Wherever possible we are certainly in favour of changing over to the " standard " system. There is general agreement that 3-phase 4-wire distribution is preferable to single-phase distribution, and the only objection to adopting the former is the presence of 3-wire mains in a network.

Mr. Romero points out that with a balanced load the conductor losses and the voltage drop on 3-core cables are 50 per cent greater on the " standard " system than on single-phase supply. This is emphasized in the paper and shown in the current vectors in Fig. 1, but provided there is a sufficiently large proportion of 4-core mains in the area to be changed over, the " standard " system renders the reduction in losses due to the use of all the cores of these 4-core mains greater than the losses due to the currents in the neutrals of the 3-core mains, thus making 3-phase 4-wire supply more efficient than single-phase supply. To illustrate this point Fig. 4 is reproduced in Fig. C, with the addition that section 8 is assumed to be a 4-core main equal in length and resistance per core to the mains in sections 1 to 6. Assuming balanced conditions and uniform loading, and provided the neutral conductors are of the same cross-section as the phase conductors, the I^2R loss on the network shown in Fig. C would be approximately 27 per cent greater on single-phase than on 3-phase 4-wire supply. It is not contended that such a network would often be met with in practice, but we consider that this example is sufficient to show that with a comparatively small expenditure the majority of 3-wire networks can be operated just as efficiently on the " standard " system as on single-phase supply.

On any network where a considerable increase of load is expected, new cables are likely to be required to meet this increase, and if such a network is being changed over to alternating current these new 4-core cables can be laid in advance and so provide for future development, and also enable the " standard " system to be adopted. We consider, therefore, that on the majority of systems —even where the network consists entirely of 3-wire mains—it should be possible to adopt the " standard " system.

Undoubtedly, however, there are special cases where it is an advantage to adopt single-phase 3-wire supply as a temporary measure. In the case cited by Mr. Romero the network evidently consisted entirely of 3-wire cables, a large proportion of which had a neutral of half the cross-section of the outers. If such a network was of sufficient capacity to meet the anticipated increase of load for a number of years, then a single-phase supply would appear to be necessary, but only as a temporary measure. In our opinion there is no justification for a permanent single-phase system, and we consider that where single-phase 3-wire distribution is adopted the delta/double-star system of transformation should be used and single-core supply maintained only until sufficient 4-core mains have been laid to enable a second change-over to the " standard " system to take place. We cannot see any objection to this second change-over, as the expense to the undertaking and the inconvenience to consumers would be very small.

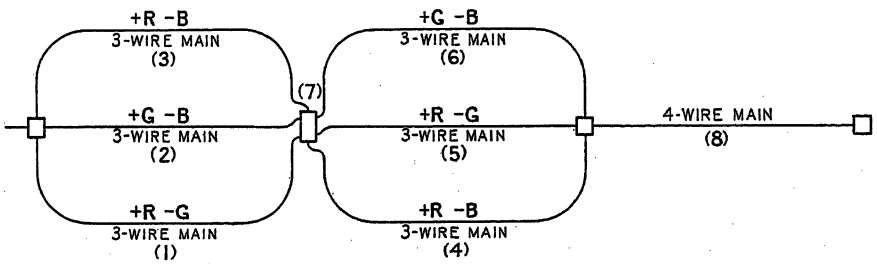


FIG. C.

Mr. Porter states that a single-phase 3-wire system will give standardization in suburban areas and that should any heavy motor loads develop special treatment would be required even on the " standard " system. This may be true, but unless these loads are sufficiently large to justify an e.h.t. supply such special treatment must include a 3-phase 4-wire supply from the l.t. network, and the only systems capable of giving such a supply are the " standard " system and the temporary single-phase system from a delta/double-star transformer.

Mr. Romero also states that single-phase supply is perfectly standard for the consumer in suburban areas. He evidently assumes that all apparatus can be dealt with on a 230-volt supply, and neglects the very serious disadvantage of single-phase supply with regard to motor loads. A reply to a question by Mr. Lees will illustrate this point.

Mr. Lees asks if the two isolated cross-shaded areas on the left of Fig. 17 are saturated manufacturing areas, and, if not, why they were not changed over with the sur-

rounding areas. These are suburban areas containing the social and shopping centres for surrounding districts. They were not changed over in 1931 because a frequency change was in progress and 50-cycle supply was not available. They are, however, being changed over this year. The southern area was given a d.c. supply by two rotary substations and one rectifier substation, the rectifier substations being situated midway between the rotary substations. The network was supplied by three 3-core feeders from one rotary substation and by one 4-core feeder and three 3-core feeders from the other. The existing 4-core mains formed approximately 29 per cent of the total mains. The 3-core feeders were reduced in length and used to give 3-phase 4-wire supply by inserting static balancers at the new feeding points. Excluding motors under 1 h.p., a total motor load of 408 h.p. had to be dealt with, and the cost of changing over the mains came within the limits shown in Fig. 7. It was not necessary, as Mr. Romero suggests, to replace all the 3-core mains. Very few replacements were required. It would have been practically impossible to supply this area with alternating current by any other than the "standard" system, and such areas are numerous in the suburban districts of a large city.

The method of distribution shown in Fig. 4 is criticized by Mr. Romero and Mr. Porter. The latter refers to this network as the ideal one for 3-phase 4-wire supply. This is not the case; it is made quite clear on page 741 that the network shown in Fig. 4 could be more efficiently supplied by the single-phase system than by the 3-phase system. Fig. 4 was inserted to show a method of giving 3-phase 4-wire supply to a network such as E in Fig. 3, where a system consisting entirely of 3-core cables is surrounded by networks suitable for the "standard" system. Although single-phase supply would be more efficient for such a network, 3-phase supply was recommended because it was obviously undesirable to insert a single-phase system in the midst of 3-phase distribution. The network shown in Fig. 4 cannot, therefore, be used as an example to test the relative efficiencies of the "standard" and single-phase systems. An examination of Fig. C will make this quite clear. As already mentioned, the network shown in Fig. 4 is reproduced in Fig. C with the addition of one 4-core main (section 8). Four-core mains form only 14·3 per cent of the total mains in this network, and yet, as previously shown, it is much more efficient to supply it by the "standard" than by the single-phase system. Referring again to Fig. 4, Mr. Romero draws attention to the losses on sections 4, 5, and 6, and states that no advantage is obtained by connecting the distributors together at point 7. He apparently assumes that when three 3-core cables are used on the "standard" system to transmit power from one point to another, the resultant flux in each of the 3-core cables produces a current in the neutral equal to the currents in the phase conductors. However, tests carried out on 3-core armoured cables 650 yards in length, with the armour bonded and earthed at the supply end only, show that the current in the neutral does not exceed 75 per cent of the currents in the phase conductors. The advantages of connecting the distributors at point 7 are:—

(*a*) In practice when sections 1, 2, and 3, happened to be unequally loaded, the total load on any one of the three phases in sections 1, 2, and 3, would be equally divided between two phase conductors for transmission back from section 7 to section 8, with a consequent reduction in losses and improvement in voltage regulation.

(*b*) Stand-by supplies are provided for the whole network in the event of the failure of any one of the sections 4, 5, or 6.

(*c*) A reduction in losses is effected amounting—in the case of balanced conditions and uniform loading—to approximately 8 per cent.

We regret an error in stating on page 5 of the advance copies of the paper, with reference to Fig. 4, that the losses would be 14·3 per cent less on the single-phase than on the "standard" system. This should be 26 per cent, and the correction has been made for the *Journal*.

Voltage Regulation.

Mr. Porter states that the ease with which local means of voltage regulation and load-balancing can be adopted on an a.c. system is one of the advantages to be obtained from changing over, whereas Mr. Preece and Mr. Jepson think that an a.c. system is at a disadvantage compared with a d.c. system as regards voltage regulation, and Mr. Carr considers the voltage regulation of an a.c. system to be inherently poor. We agree with Mr. Porter, and consider the voltage regulation of an a.c. system to be superior to that of a d.c. system. This seems sufficiently proved by the fact that when supply authorities lay down a d.c. system they provide means for controlling the voltage either automatically or manually, whilst the present practice is to lay down an a.c. distribution centre without means of automatic voltage control and assume that the voltage regulation will take place on the l.t. network. The result is that the voltage is maintained constant at the l.t. busbars in the d.c. substation, whilst the a.c. distribution has to be of sufficient capacity to provide for variations of the e.h.t. supply voltage. To provide a fair comparison, the regulation on the l.t. networks only should be considered. The smaller cost of an a.c. centre compared with that of a d.c. centre makes the radius of supply in the case of the former usually less than one-third that of the latter. As the voltage-drop is proportional to the radius of supply, the drop on the low-tension a.c. distribution is usually less than half that on the low-tension d.c. network, even after allowances have been made for power factor, inductive drop, etc.

One of the principal causes of poor voltage regulation is unbalanced conditions on the l.t. network. On an a.c. system the out-of-balance current can be easily and cheaply corrected by inserting a static balancer where required. If the low-tension a.c. network is not of sufficient capacity to give reasonable voltage regulation there seems no reason why automatic a.c. voltage regulators should not be installed. Such regulators are objected to because they are so expensive compared with the cost of a transformer: this objection seems to be based not on the excessive cost of the regulator but on the cheapness of the transformer. Referring to Fig. 9, if it is assumed that the cost of an automatic voltage regulator for a 500-kVA transformer is £200, then the

total cost per kW of site, building, and equipment, including the regulator, would be less than £3 per kW for an a.c. centre. When this figure is compared with the equivalent cost for a d.c. centre of between £12 and £13 per kW, there seems no reason on the score of expense to object to the installation of a.c. automatic voltage regulators.

We, of course, agree with Mr. Preece that a cheaper a.c. automatic voltage regulator would be a decided advantage, and we consider that it might be advantageous if supply authorities had means of automatic voltage regulation incorporated in all new transformers installed.

Power-Factor Correction.

We agree with Messrs. Romero, Howarth, Swale, and Mellonie, as to the advantage of giving consumers a financial interest in the maintenance of a good power factor. On page 746, col. 2, of the paper it is pointed out that some supply authorities are introducing preferential terms for good power factor, and should this practice continue difficulties resulting from a poor power factor will tend to diminish. The suggestion to install power-factor-correction plant at master substations was only intended as an additional remedy should the preferential tariffs mentioned above not prove sufficient. In such a case it would obviously be impossible, as Mr. Chattock points out, to install power-factor-correction plant at low-tension consumers' premises, as the majority of consumers affected would have a maximum demand of from 5 to 30 kVA.

We agree with Mr. Howarth that, if it can be accomplished at a reasonable expense, it is better to correct the power factor on the low-tension than on the high-tension side of the step-down transformers. Unfortunately, to install power-factor-correction plant at every distribution centre would be rather a costly business, and for this reason we suggest that where necessary power-factor-correction units of large capacity be installed at certain selected master substations.

Mr. Rawll states that preferential terms for good power factor are usually restricted to extra-high-tension consumers; but Mr. Romero and other speakers give instances of where such terms have been granted to low-tension consumers. Replying to Mr. Penrose, we are of the opinion that preferential tariffs for good power factor should be adopted by all undertakings giving a low-tension a.c. supply.

Mr. Orme asks at what horse-power it is more economical to install a synchronous motor than an induction motor. This depends upon the power factor of the remainder of the consumer's load and on the preferential terms granted by the supply authority.

Substation Sites.

Mr. Forster asks for some idea of the cost of substation sites. It is quite impossible to give an average figure, as this cost varies to such an extent even in one district. Where the site is required for a new housing estate in a suburban area it is in the interest of the owners of the land to sell at a reasonable price, because the substation is usually necessary to supply houses which the vendors of the site are building: in such cases the cost is usually between 3s. and 8s. per square yard. Where the site is required in a built-up suburban area and the vendor has no interest in the supply of electricity to the surrounding district, he may try to obtain three or four times this amount. In city areas where land is very scarce very high figures per square yard may be asked for the small plot of land necessary for an a.c. substation. The costs given in the paper are only comparative, and it is possible to assume an average price per square yard because the cost per square yard for a site is the same whether an a.c. or a d.c. substation is erected.

We are glad that Mr. Townley agrees with our view that more definite, speedy, and direct powers for the removal of restrictive covenants and the acquisition of substation sites are urgently required.

Advantages to Consumers Resulting from a Change-Over.

Messrs. Romero, Swale, Porter, and Penrose, point out the advantages to be gained by a consumer from a change-over to alternating current. We are glad that this point was raised, as undoubtedly it is not sufficiently stressed in the paper, which deals principally with the change-over from a supply undertaking's point of view. This point was not entirely lost sight of, however; the extracts from the *Electrical Review* (on page 748) were inserted partly to point out this advantage. Further, it is stated on page 749, with reference to these extracts, . . . "The report further indicates the advantages to be obtained by an industrial consumer from a change-over to a.c. supply, the importance of which is obvious both from the individual and the national point of view."

We cannot agree with Mr. Carr when he states, with reference to the extracts from the *Electrical Review*, that the change-over at the Ford motor works is not comparable with a change-over carried out by a supply undertaking. It seems obvious that the Ford Motor Co. have a private e.h.t. transmission system, and among the benefits claimed in the report are reduction in energy losses in distribution lines and in conversions to direct current, and reduction in substation operation labour. Surely these are some of the principal benefits resulting to a supply undertaking from a change-over.

Mr. Orme thinks that a consumer should not contribute towards the cost of replacements rendered necessary by a change-over, whilst Messrs. Carr, Swale, and Penrose, consider that he should shoulder some of the burdens which fall upon the supply industry. We take the latter view, as in many cases the consumer's obsolete and inefficient d.c. plant is replaced by new, efficient a.c. plant. Further, the installation of a.c. plant reduces his maintenance charges by about 80 per cent. The change-over is therefore of definite financial value to the consumer, and it seems only reasonable that he should contribute towards its cost.

In the discussion at Birmingham Mr. Shaw gave several instances of consumers who, having had the facts placed before them, did contribute towards the cost of changing over. We are of the opinion that by adopting the methods described by Mr. Shaw and getting into touch with consumers beforehand, a very considerable saving in change-over costs can be effected.

Use of Feeders on A.C. Systems in Suburban Areas.

Mr. Romero and Mr. Carr take exception to the use of feeders on a.c. systems, and the former advocates a system of large distributors all of the same size. As Mr. Chattock points out, such a system would be possible if a new network were being laid down, but, unfortunately, existing distributors are too small in the majority of cases to provide for future requirements or even to meet present demands in the manner suggested by referred to in the paper and the old d.c. feeder system. There is, however, no fair basis of comparison between the two. Many d.c. feeders were over 1 000 yards in length, whilst the a.c. feeders are very short, the length being dependent upon the geographical lay-out of the area of supply. The use of these short feeders entails the loss of none of the advantages of a.c. distribution. If preferred, they can be tapped and used as feeder distributors, but we do not regard this as advisable.

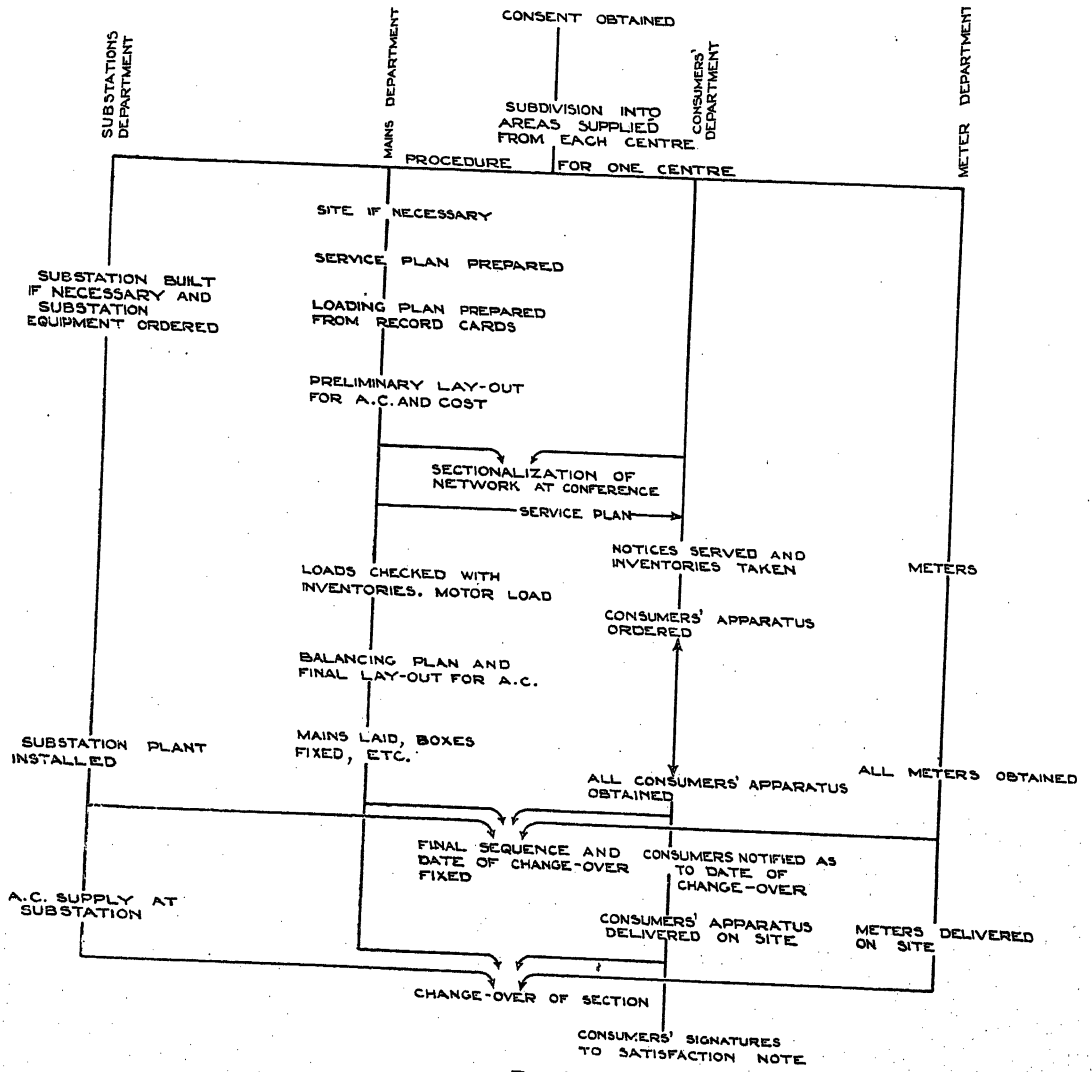


FIG. D.

Mr. Romero. New cables are therefore required to provide an outlet from distribution centres, and, as far as changing-over or any of the comparisons or costs given in the paper are concerned, it is immaterial whether these cables are used as feeders or feeder distributors. ncidentally, we consider that for suburban areas a etwork with short feeders and a uniform size of distributor is more economical than the feeder-distributor ystem recommended by Messrs. Beard and Haldane.

Mr. Carr draws a comparison between the system

Procedure in Carrying Out Change-Over.

We agree with Mr. Townley that careful organization is very important, and indeed absolutely essential, if the change-over is to be successfully carried out. A diagram giving a suggested model procedure for changing over the supply area of one distribution centre is shown in Fig. D.

In reply to Prof. Cramp and Mr. Harber, where it is neither possible nor convenient to replace d.c. apparatus with a.c. apparatus, the practice is to install converting

or rectifying plant to operate the existing d.c. apparatus. D.C. eliminators are operated by suitable rectifiers or are replaced by equivalent a.c. eliminators.

With reference to Mr. Howarth's inquiry regarding the bringing of old installations up to date, in factories where the new conditions of supply necessitate alterations to the installation, in order to comply with the Home Office Regulations, such alterations are carried out by the electricity department. As regards private dwelling-houses, under the I.E.E. Wiring Regulations all switches above conducting floors, whether used on 230-volt d.c. or 230-volt a.c. supplies, should be either earthed or shockproof, and quite apart from the change-over an endeavour is made to induce consumers to adhere to this rule.

In reply to Mr. Sammons, Fig. 18 shows a running total of the number of consumers changed over. Thus in 1931 approximately 12 000 consumers were transferred from d.c. to a.c. supply. We imagine that it would be rather beyond the powers of any supply authority to change over 26 000 consumers in any one year. Although in Birmingham the system is actually being changed over from 220-volt d.c. to 230-volt a.c. supply, we are at a loss to understand how Mr. Sammons comes to credit us with the statement in connection with the paper that 220-volt apparatus was connected to the 230-volt a.c. supply. We made it quite clear that in the preparation of the paper the question of alteration to the voltage of supply was not considered.

In reply to Mr. Fay's question as to how many meter fixers are necessary to change over 240 meters in one day, our estimate is approximately 8 men and 6 youths.

We agree with Mr. Stewart that in suburban areas a considerable saving in expenditure can sometimes be effected by connecting lengths of a 3-wire main to a 4-core distributor, instead of transferring all the services to the 4-core cable.

In reply to Mr. Sowman, motor convertors, rotary convertors, or rectifiers, are only installed by arrangement with the consumer, whose property they become and who is responsible for their maintenance. The metering takes place on the input side.

We are glad that Mr. Steel, Mr. Rawll, Mr. Penrose, and other speakers, support our view that in all areas only 4-core cables should be laid.

Utilization of 3-Core Feeders on the " Standard " 3-phase 4-wire A.C. System.

Mr. Fay asks what is the best method of utilizing existing 3-core feeders on the " standard " a.c. system, and Mr. Rawll suggests that the bunching of 3-core feeders to form one 3-phase feeder should only be used as a temporary expedient. On page 741 four methods are suggested whereby 3-core feeders can be used to give a 3-phase 4-wire supply: viz. by bunching two or more 3-core feeders together; by running a fourth wire; by inserting static balancers at the feeding points, and as phase boosters in conjunction with 4-core feeders. The first two methods are not recommended except as a temporary arrangement where the feeders are very short and the load very light, but by using either of the other two methods a satisfactory permanent arrangement is obtained. In our opinion the best method of utilizing a 3-core feeder on a " standard " a.c. supply is to reduce the length of the feeder, insert a static balancer at the new feeding point, and use the remaining part of the feeder as a phase booster on the network. The total cost of supplying and installing at the feeding point of a 3-core feeder a static balancer capable of dealing with an out-of-balance current of 100 amperes is approximately £35, and provided the cores are all of the same cross-section the carrying capacity of the feeder is thereby increased by 50 per cent. A static balancer may not be necessary where a network is supplied from the same substation by a 3-core feeder and a 4-core feeder. Practically full use can be made of the former by using it as a phase booster in parallel with the latter.

In reply to Mr. Fay's inquiry regarding voltage-drop, when a heavy out-of-balance current has to be dealt with by a 3-core feeder used in conjunction with a static balancer, the neutral point of the balancer may be slightly displaced, resulting in an increased voltage-drop on one of the phase conductors of the feeder.

With reference to Mr. Forster's remarks regarding the use of static balancers for individual consumers, where a power and lighting consumer is supplied by a long 3-wire service a static balancer is sometimes installed at the consumer's premises in preference to relaying the service.

Standardization of Voltage.

We cannot agree with Mr. Rawll when he states that the standardization of voltage is more important than the standardization of the type of current supplied. From a supply undertaking's point of view the advantages to be obtained from standardization of voltage are not comparable with those to be derived from a change-over from d.c. to a.c. supply. Standardization of voltage benefits principally the consumers of electricity and the manufacturers of electrical apparatus, but the supply industry should also benefit to a large extent by a reduction in the cost of certain apparatus (e.g. transformers) and by an increase in the consumption of electricity. For this reason we agree with Messrs. Rawll and Swale that when a change-over takes place only the standard a.c. voltage of 230 volts between phase and neutral should be adopted. This is stressed on page 754 of the paper.

Switchgear.

In reply to Messrs. Pegg and Mellonie, the costs given in the paper are for comparative purposes and allow for a similar type and class of switchgear for both alternating current and direct current, the rupturing and carrying capacity being the same for both systems of supply. For suburban areas (Figs. 7, 9, 10, and 11) the costs are based on distribution centres of 500-kW unit capacity. For city areas (Figs. 14, 15, and 16) the expenditure is based on substations of 2 000-kW unit capacity. As the costs are given in £ per kW, the capacity could be multiplied or the class of switchgear altered without materially affecting the comparative costs, provided the same type and class of switchgear were still maintained for both a.c. and d.c. supply.

Relative Lives of A.C. and D.C. Networks, and Comparison of Mains Faults on Alternating and Direct Current.

Mr. Townley asks for more information regarding the network of a supply authority in the North Midlands, which is referred to in the paper. Mr. C. H. Yeaman, chief engineer to the Stoke-on-Trent undertaking, has kindly supplied us with the following information:—

"The network referred to was laid between 1905 and 1910 and was changed over to alternating current in November 1923. The system, which originally operated on 3-wire d.c. supply, consisted of three single-core cables laid side by side on wooden bridges covered with bitumen in wooden troughs with tile covers. The cables were composed of stranded conductors insulated with vulcanized bitumen and braided. The nature of the soil in which the cables were laid varied. The ground originally had been undulating and it had been the practice to level it up partly by removing soil from the high places and filling up the low, and partly by filling in with house-refuse, boiler clinker, broken pottery, or anything else that happened to be available. The average number of faults on d.c. supply was approximately 12 per annum, but during the latter years of the life of the d.c. system faults occurred at intervals of approximately one week during certain months. Since the change-over to alternating current 9 years ago practically the only faults which have occurred have been due to mechanical damage, and during the last 3 years there have been no faults. The effect of changing over this network was so marked that the principle was adopted generally, with complete success."

Mr. Townley asks what is the probable life of a distribution network, both on alternating and on direct current. The life of any l.t. network depends to a large extent upon the nature of the soil in which the cables are laid, and we do not think that sufficient information is available to enable an estimate to be made of the probable life of modern cables on a.c. supply. The information supplied by Mr. Yeaman, however, indicates that the life of such a network laid in soil of the kind described above is approximately 17 years on d.c. supply and probably 40 to 50 years, or even longer, on a.c. supply. We therefore appear to be justified in assuming that the life of an a.c. system would be at least double that of a d.c. system under similar conditions.

In reply to Mr. Romero, we have not sufficient information at our disposal to enable us to give a comparison of mains faults on a.c. and d.c. supplies so far as multi-core armoured cables are concerned, but the relative figures of 10·8 faults on a d.c. system and 0·99 on an a.c. system, per 100 miles of distribution per annum, were obtained from networks in which a fair proportion of the cables were of the multi-core armoured type.

Mr. Sammons thinks that 10·8 faults per annum on a d.c. system compared with 0·99 per annum on an a.c. network is a very unfair comparison, and assumes that these figures were obtained from a d.c. system consisting entirely of old vulcanized bitumen cables and an a.c. network of new paper-insulated cables. This is not the case. The a.c. and d.c. networks were laid in adjoining districts and the former had been in operation for nearly 30 years; many of the cables operating on alternating current had also been laid for that time. There was a greater proportion of armoured cables in the d.c. network than in the a.c. system, so that we regard the comparison as quite fair.

We cannot agree with Mr. Sammons that similar cables properly laid will last just as long on a d.c. as on an a.c. system. This question is settled by the information given above and supplied by Mr. Yeaman, which refers to a network where there was no difference in the type of cable, nature of soil, or method of laying, as the same cables were used on both d.c. and a.c. supply. After about 17 years of d.c. working this network was in such a state that total replacement was under consideration. Instead, it was changed over to alternating current, and faults and maintenance troubles disappeared. We consider it beyond doubt that under similar conditions the number of faults and the maintenance charges on an a.c. network are very much less than on a d.c. network.

Development.

Mr. Romero does not agree with our estimate of 15 per cent per annum for the rate of increase in the demand for electricity. It should be remembered that this estimate is not inclusive of e.h.t. power load, but refers to l.t. networks in suburban areas where the demand consists chiefly of domestic load. In 1926 Messrs. Beard and Haldane stated:* "The future of electricity supply, particularly as regards domestic load, will bring not a slow development but a rapid growth which will at least double and possibly quadruple existing loads within the next 10 years." We consider that during the last 6 years the growth in the demand for electricity for domestic purposes, particularly in suburban areas, has more than justified this view, and we do not see any reason for anticipating a reduction in the rate of increase of load. We must therefore differ from Mr. Romero and suggest that 15 per cent per annum is a reasonable estimate of the rate of increase in the demand for electricity on l.t. networks in suburban areas.

Change-Over in City Areas.

We are glad to have Mr. Brazil's and Mr. Chattock's support for our view that the best method of providing a.c. supply for city areas already developed on direct current is to superimpose a 4-core network on the existing 3-wire network, but we do not agree with Mr. Brazil that the d.c. load should be allowed to develop until the loading on the 3-wire distributors approaches the maximum. The loading and condition of both the 3-wire network and the d.c. converting plant have to be considered, and the latter is probably the more important consideration. Local conditions must, of course be the deciding factor, but in general no additional d.c. converting plant should be installed or any existing converting plant replaced. When such plant requires replacement, sufficient load should be changed over to alternating current to make the replacement unnecessary. If this is done there will probably not be sufficient capacity of d.c. plant to provide for the new d.c. feeders mentioned by Mr. Brazil, and we are of the

* "The Design of City Distribution Systems, and the Problem of Standardization," *Journal I.E.E.* 1927 vol. 65, p. 97.

opinion that it is better to develop a new a.c. network where necessary instead of laying additional d.c. feeders.

The initial expense of starting an a.c. system and changing over sufficient load may be greater than the cost of laying a d.c. feeder, but the aim should be ultimately to obtain a complete a.c. system with the resultant advantages of reduced capital, maintenance, and development charges, and increased life of plant and network. Unless a permanent d.c. system is to be maintained, every kW of additional load connected to the d.c. network increases the change-over costs of the undertaking. We realize, of course, that it may be many years before a complete 4-core network can be superimposed on the existing 3-wire network, and that during this period additional d.c. load will have to be added in certain areas, but we suggest that the total d.c. load should be gradually reduced until ultimately a complete a.c. system is obtained. Where new d.c. connections must of necessity be made, consumers should be persuaded to install wiring and, as far as possible, switchgear and plant suitable for 3-phase 4-wire a.c. supply.

In reply to Mr. Swale, we think that, where local conditions permit, heating and lighting loads should be changed over to alternating current first of all, and that connections which are costly to change should be left on d.c. supply as long as possible. In the meantime opportunities may arise—owing to replacement of plant, reorganization of works, or transfer of ownership—of carrying out the change-over at a greatly reduced cost.

Mr. Fay's point that two of our suggestions (one on page 747 and the other on page 750) are inconsistent has been dealt with in our reply to Mr. Brazil. We see nothing inconsistent in these two suggestions, but the following example which embodies both should make this clear. Assume that the plant in a d.c. distribution centre is becoming overloaded, and that one or more a.c. systems are started on the periphery of the d.c. area of supply and some of the load changed over to alternating current. The d.c. load on the centre is thus reduced, and if the feeders are shortened an increase of load on the remaining d.c. network can be dealt with, without extending the d.c. plant in the centre or laying additional d.c. feeders. As the load on the remaining d.c. network further increases, or the d.c. plant requires replacement, the a.c. network is extended and the d.c. network reduced until ultimately a complete a.c. system is obtained.

Regarding Mr. Fay's suggestion to refuse to connect up consumers on a d.c. supply unless they agree to indemnify the supply authority against the cost of changing over, we are afraid that undertakings are not in a position to refuse power or lighting load or to compel consumers to make such an agreement unless they intend to carry out the change-over within a reasonable time after connecting up the consumers concerned.

Mr. Shackleton must have misunderstood our reference to secondary batteries. Although in putting forward the relative merits of the a.c. and d.c. systems we stated that there was nothing on the former to replace the secondary batteries in use on the latter, we gave reasons (page 747) for not considering the loss of secondary batteries any disadvantage to a.c. distribution.

Cost of Changing Over.

Mr. Ripley and Mr. Penrose consider that the costs given in the paper are not representative, and Mr. Lees states that the expenditure on consumers' apparatus for suburban areas is excessive. It is quite true that the cost of changing over in different areas varies with the nature of the l.t. network, the density of the load, the type of property, and the nature of the load supplied. The costs given in Part 1 of the paper are average figures computed from actual results obtained when changing over some 30 different suburban and residential areas. A detailed examination of this expenditure shows that although the total cost of changing over one area may differ very much from the total expenditure necessary to change over another area, yet where there is an excessive amount of apparatus requiring alteration there is usually a corresponding amount of apparatus which requires no alteration and entails no expense, so that, excluding the expenditure for alteration to wireless apparatus, the cost per kW based on maximum demand does not vary to a large extent. The costs in Figs. 7, 9, 10, and 11, were only inserted to indicate the undoubted economic advantage of changing over to a.c. supply, and we are of the opinion that they are sufficiently accurate for that purpose.

The cost per kW demand for alterations to wireless apparatus remains fairly constant in the different areas at any one time, but, as shown in Fig. 19, this expenditure has rapidly increased during the last few years and now forms a large proportion of the total cost of changing over. If the expenditure on wireless apparatus be excluded, we do not agree with Mr. Ripley that the cost per kW demand of changing over will increase in the future. A large increase in the demand for electricity for heating and cooking purposes is to be expected, and provided no change in effective voltage is involved the change-over of this type of apparatus entails no expense. Such an increase of load, therefore, should reduce the cost per kW demand of changing over and more than compensate for the increased expenditure necessary to change over additional connections of apparatus which requires alteration. We agree, however, with Mr. Ripley that the 7-year loan period adopted by the Electricity Commissioners for the cost of changing over consumers' apparatus could with advantage be greatly extended.

Mr. Ripley suggests that the economics of rectifier substations should be investigated in connection with small towns which are generating direct current and are to take a supply from the "grid." We are quite sure that an investigation of the capital cost and maintenance and development charges will only serve to emphasize the economic advantage of changing over.

The percentage costs given by Mr. Ripley for changing over in a residential town are very interesting, but they would have been more so had it been possible to compare them with the costs given in Fig. 7. Unfortunately Mr. Ripley only gives an analysis on a percentage basis, and does not state the actual cost per kW demand or per kW installed. Further, his cost for changing over mains includes expenditure on e.h.t. cables, which for obvious reasons has not been included in Fig. 7. His detailed analysis of the expenditure on consumers' apparatus in a residential district seems to show an

excessive amount for changing over motors and motor equipment. He appears to have been very fortunate, however, in the small amount of wireless apparatus with which he has had to deal.

Mr. Penrose considers that the costs given in Fig. 14 for changing over consumers' apparatus are too low, his reason for this view being that in Manchester the costs obtained for conversion of apparatus in industrial areas were in excess of those obtained for residential areas. We understand that in the suburban areas referred to no wireless apparatus was changed over, and if such is the case the results obtained in Manchester would appear to confirm the costs given in Figs. 7 and 14. An examination of these figures will show that the costs for conversion of consumers' apparatus in industrial areas is approximately three times that for residential areas if the expenditure on wireless apparatus be excluded. No allowance is made in Fig. 14 for relief in respect of change of frequency.

In reply to Mr. Rawll, the estimated costs given in Fig. 14 include the expenditure necessary for re-wiring consumers' premises. With reference to the low cost for maintenance on an a.c. system mentioned by Prof. Cramp, the figures given in Fig. 8 include all charges for repairs, renewals, inspection, and a fair proportion of overhead charges. These costs were inserted for comparative purposes and were computed on the same basis as the costs given for the d.c. system, but the a.c. system from which they were obtained is capable of dealing with a considerable increase of load. As the load increases, the maintenance costs per kW demand will fall. We consider, therefore, that the maintenance charges for an a.c. system given in Fig. 8 could be considerably reduced.

Mr. Shackleton considers that it would have been better to have stated the costs of changing over in £ per kW of connected load, instead of per kW demand. The only costs that could have been conveniently stated in terms of connected load are those for conversion of consumers' apparatus. One of the principal objects of the paper was to show the economic advantages to a supply undertaking of changing over from direct to alternating current, and it was necessary for comparative purposes to reduce all expenditure to a common basis. All the capital expenditure and a large percentage of overhead and maintenance charges of an undertaking are based on maximum demand, and even had the conversion charges for consumers' apparatus been stated in terms of connected load it would have been necessary to have converted them to £ per kW demand for comparative purposes. For a general survey of the subject of change-over, the total expenditure on conversion of consumers' apparatus is relatively unimportant. What really matters is the cost in relation to the other costs of changing over, and also in relation to the reduction in expenditure resulting from a change-over. We consider, therefore, that it is better to state the change-over costs in terms of maximum demand than in terms of connected load.

In reply to Mr. Stewart, the estimates given include the costs of transferring services to new 4-core distributors.

Mr. Porter considers that the advantages of changing over to a.c. supply should be amplified by the inclusion of the elimination of substation attendance costs and the reduction of maintenance charges on vulcanized bitumen cables. The latter advantage is shown in Fig. 8, where the maintenance charges on cables in d.c. and a.c. networks are compared. These costs were obtained from systems which included a large proportion of vulcanized bitumen cables. While we agree that the elimination of substation attendance costs consequent upon changing over is a very important financial advantage, it was necessary for comparative purposes to reduce all the costs given in the paper to unit values, and it is impossible to give substation attendance charges in terms of £ per kW. Thus, although the capitalized value of the attendance charges on a 2 000-kW substation may be £20 000, attendance might be provided for a 10 000-kW station for the same sum. We therefore had to eliminate labour charges, and all the costs given for d.c. centres refer only to those which are automatically controlled. As the capital expenditure given in Figs. 9 and 15 for d.c. centres includes the cost of automatic gear, which is an important item, it would have been unfair to have put forward as an additional advantage the elimination of attendance charges on non-automatic d.c. centres.

Mr. Rawll considers that the value of displaced d.c plant is not worthy of consideration. No credit in this respect is allowed in any of the costs put forward, and it is only mentioned—as an additional advantage of changing over—that in certain circumstances the value of such displaced plant could be credited to the change-over. It is not always convenient to start a change-over in an area where the existing d.c. plant is becoming overloaded. Converting plant displaced by the change-over in another area can be installed as a temporary measure until a change-over can be commenced, and thus the necessity of buying new plant may be prevented. In such a case the amount which could be credited to the change-over in respect of displaced d.c. plant would be very considerable.

Mr. Rawll states that as the cost of change-over bears no relationship to the revenue to be derived from the increase of load which is to be expected, he fails to understand why in approximately 5 years the total cost of changing over should be recovered from development charges alone, assuming an annual load increase of 15 per cent. He appears to be confusing the expenditure necessary to meet additional load with the revenue derived from this load after it is connected. As the load increases, new substations, substation equipment, mains, and meters, are required to deal with it. The costs of such buildings and equipment are much less on an a.c. than on a d.c. system. Thus after an area has been changed over the expenditure necessary to meet an increase of load is much less than if the system had remained on direct current. This reduction in development charges is one of the principal advantages to be obtained from changing over.

In reply to Mr. Rawll's question regarding Fig. 8, subdivision 4 includes the maintenance charges on services, main switches, and hired apparatus. This item is met by all supply undertakings. It would perhaps have been better had we referred to this subdivision as

"installation equipment" instead of as "consumers' apparatus."

Liability of Central Electricity Board.

Messrs. Lees, Rawll, and Stewart, draw attention to the statement on page 738 that the Central Electricity Board may have power to compel small d.c. generating authorities to shut down their plant and take a supply from the national "grid." We regret that when the paper was being prepared we were misinformed regarding the powers conferred on the Central Electricity Board by the 1926 Act, and we now understand that the Board have no power to compel an undertaking to shut down their plant and take a supply from the grid.

The statement referred to was inserted in order to illustrate the advantages to be obtained by a small d.c. authority from changing over to l.t. alternating current immediately 50-cycle high-tension supplies are made available by the "grid." Unfortunately, we chose the case of a small authority generating its own supplies, but a small undertaking receiving bulk supply at a frequency other than 50 cycles per sec. and converting to l.t. direct current for its own use would have illustrated our point just as well. If such a case be considered, then when the standardization of frequency takes place the Board will be responsible for the total cost of the alterations necessary to make the converting plant suitable for operation on a frequency of 50. If, however, the undertaking decided to change over the l.t. supply from direct current to 50-cycle alternating current at the same time as the change of frequency, then the converting plant would be discarded and no alterations would be necessary. We understand that in such a case the undertaking might receive a certain percentage of the estimated cost of the alterations to the converting plant, and this sum could be used towards the cost of the l.t. change-over. If, therefore, in the statement on page 738 the case of a small undertaking receiving bulk supply at a frequency other than 50 cycles per sec. and converting it to direct current for its own use be substituted for that of a small township at present generating direct current for its own use, then a slightly modified form of the costs given in Table 2 will apply.

We are of the opinion that it is to the advantage of the Central Electricity Board to encourage supply authorities to carry out a low-tension change-over concurrently with a change of frequency. Where the frequency of the h.t. supplies to a converting or rectifier station is being changed to 50 cycles per sec., the Board are responsible for the total cost of making the plant suitable for the standard frequency. If instead of continuing d.c. supplies a low-tension system change-over is carried out, an undertaking would probably accept about three-quarters of the estimated cost of changing the frequency on the converting or rectifier plant. A saving of about one-quarter of the total cost of the frequency change on the converting or rectifier centre would thus be effected by the Board, and the undertaking would receive a considerable contribution towards the cost of the l.t. system change-over.

Mr. Stewart credits us with stating on page 738 that the Board bears the cost of converting d.c. supplies to a.c. supplies. No such statement is made in the paper. As explained above, we suggested that in certain circumstances a sum received from the Board in respect of frequency change might be used towards the cost of changing over from d.c. supplies to a.c. supplies. As there may be some misunderstanding on this point, we wish to make it clear that we do not suggest that the Board are in any way concerned with or responsible for the change-over from direct current to alternating current. With the exception of those in Table 2, none of the costs given in the paper include or allow for any contribution from the Board.

Use of Single-Core Cables on Alternating Current.

In reply to Prof. Cramp, there are practically no single-core armoured cables in use in Birmingham as distributors, but a considerable number of the feeders in use on direct current in the city and industrial area consist of three single-core lead-covered and armoured cables of 1 sq. in., 0·5 sq. in., 1 sq. in. cross-section. We agree with Prof. Cramp that these feeders could not be changed over to alternating current. This fact is allowed for in Part 2 of the paper, as the network recommended for city and industrial areas consists entirely of 4-core cables.

Mr. Ripley asks for information regarding the use of single-core armoured cables on alternating current. Apart from the increased inductance drop, on account of the excessive losses we consider it inadvisable to use these cables as feeders or distributors on any type of a.c. supply. Three single-core lead-covered unarmoured cables can be used to a limited extent on single-phase alternating current, provided the cables are laid very close together.

Motors.

In reply to Mr. Ripley and Mr. Fay, the limits to the size of single-phase motors depend upon local conditions, i.e., the capacity of the l.t. network, the cost of relaying the service or altering the service connections, and upon whether a 4-core distributor is available. Generally speaking, where a 3-phase 4-wire supply is available in suburban areas we consider that motors of 1 h.p. and above should be connected to the 3-phase supply. In special cases where there is no 4-core distributor, single-phase motors of 2 h.p., or sometimes 3 h.p., may be permitted, but these are usually of the repulsion induction type operating on 400 volts and have a limited starting current.

Mr. Rawll considers that the disadvantage of the single-phase system with regard to the supply of motor loads should have been included in Table 3. This table only gives a comparison of the different methods of transformation from 3-phase high-tension supply to single-phase low-tension supply. The difficulty in the supply of motor load is common to all single-phase systems, and a special paragraph on page 742 is devoted to this disadvantage.

MODERN COMMUNICATION SYSTEMS.

By Dr. F. LÜSCHEN.

(*Paper received* 14*th January*, 1932; *read before* THE INSTITUTION 7*th April, and before the* NORTH-WESTERN CENTRE 5*th April*, 1932.)

SUMMARY.

In the first part of the paper the principles underlying modern communication engineering are discussed. The second part of the paper deals with some characteristic examples of the multiple utilization of transmission systems, such as 2-band systems and simultaneous telephony and telegraphy using short waves.

New inventions and the tendency to economize on working facilities have made the design of modern communication systems very complicated. The interconnection of wire and wireless systems, for the first time carried out in the connection of Great Britain with the United States, the multiple utilization of lines for telegraphy and telephony, and for the purpose of remote control in the domain of power transmission, together with the electro-acoustic transmission problems involved in broadcasting and talking-films, have enormously extended the field of use of communication systems.

While the practical systems are becoming increasingly complicated, theoretical scientific research work has reduced the solution of the inherent problems to formulæ which permit of a simple computation of the systems. These fundamental considerations deal in particular with that part of the communication system which, strictly speaking, serves for the transmission of information. Though in the early days of telegraph and telephone engineering this part (called the "transmission equipment") was made up only of one or two wires between transmitter and receiver, from a physical standpoint it is actually the most complicated part of the system. It will be dealt with in detail in the following section.

PRINCIPLES OF COMMUNICATION ENGINEERING.

Transmission systems are designed to transmit information, the latter being represented by a definite magnitude-time function of the voltage and current applied at the input of the transmission system; the system is so designed that the current and voltage at the output, regarded as a time function, enable the message to be recognized. The information embodied, for instance, in the spoken word is a temporal sequence of vowels and consonants and is an extremely complicated function of time. The transmission system is in general composed of widely differing elements, so that it seems almost hopeless to describe the manifold variations which the information suffers on being transmitted. Nevertheless, we have succeeded in visualizing the transmission with the help of a few principles.

A very simple and fruitful manner of dealing with the problem is based on the knowledge that the information to be transmitted can be represented by Fourier's integral as the sum of an infinite number of steady-state, sinusoidal, frequency components. The information is thus characterized by its oscillatory components—strictly speaking by the amplitude, frequency, and phase, of these components—and the variations of the message during the transmission process may be deduced from the behaviour of the system for steady-state components.*

Experience has shown that the reproducible transmission of information, whether by way of the telegraph or of the telephone, does not require the whole frequency band; a restricted band, including only those components which enable the message to be recognized, is all that is required. This restricted band is not dependent on the transmission system, but only on the nature of the message. This knowledge has led to two important conclusions. The first is that the transmission of information is determined only by the characteristics of the system with respect to the required band width. The second refers to the relation between the transmission speed of a message and the width of the frequency band. It is generally possible to alter the frequencies to be transmitted; this is done by storing the message currents on a steel wire, a gramophone disc, or a sound film, and then picking up the message with a modified velocity of the storage device. A reduction of the velocity to half its value, for instance, means that each frequency contained in the message is halved. A proper choice of the velocity permits of enlarging or narrowing the frequency band to any desired amount, but the time required for the transmission of a given quantity of information increases or decreases in the same ratio. This is one of the most important principles discovered during the last 10 years. Hartley† expresses it as follows: "The total amount of information to be transmitted over a system is proportional to the product of the frequency range which it transmits by the time during which it is available for the transmission." It is, for instance, altogether impossible to construct a device which will halve all the frequencies contained in the information and yet leave the rate of communication unaltered. The endeavour of numerous inventors to obtain a more efficient transmission system by continuously narrowing the speech band at the system input and widening it at the output, will always remain unfruitful.

* O. HEAVISIDE: "Electromagnetic Theory," vol. 1; also J. R. CARSON: "Theory of the Transient Oscillations of Electrical Networks and Transmission Systems," *Transactions of the American I.E.E.*, 1919, vol. 38, p. 345.

† R. V. L. HARTLEY: "Transmission of Information," *Bell System Technical Journal*, 1928, vol. 7, p. 535.

Transfer Exponent.

The characteristics of any transmission system with respect to the sinusoidal components contained in the message may be represented by two quantities, the attenuation and the phase difference. To each oscillatory component at the input of the system there corresponds a component of equal frequency at the output, if the transmission characteristics of the system are independent of time. In general, the oscillations at the input and output differ in magnitude and phase. The ratio of the amplitudes of the voltages or currents at the input to those at the output of the system, for any given frequency, is expressed by the equation

$$a = e^{\alpha}$$

where α is the attenuation of the system. The phase difference between the two oscillatory components is represented by β. The two quantities α and β can readily be calculated or measured; they give a clear insight into the transmission characteristics of the system.

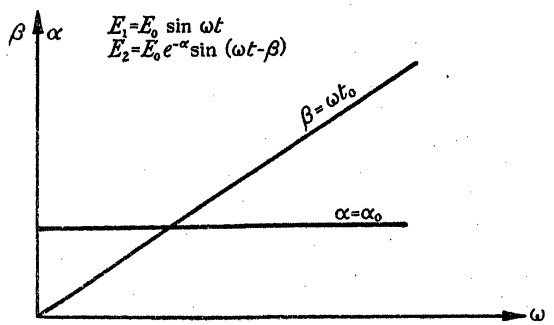


FIG. 1.—Attenuation and phase of distortionless system.

Assuming for all frequencies that $\alpha = 0$ and $\beta = 0$, the components at the output of the system would coincide with those at the input. The received message currents would be identical and simultaneous with the transmitted ones; their magnitude/time functions would be equal. These two conditions characterize the ideal transmission. Now it is physically impossible to transmit information between two distant points without any delay. Provided that all the oscillatory components are delayed by the same amount on being transmitted, the shape of the message currents remains unaltered. This is the case if the phase difference β of the components increases linearly with frequency. On the other hand, the shape of the message currents remains the same if all the components are attenuated or amplified in the same ratio, i.e. if the quantity α is of constant value for all frequencies. In this case the transmission is considered to be distortionless; thus the fundamental conditions for distortionless transmission are as follows:—

$$\alpha = \alpha_0 = \text{constant}; \quad \beta = \omega t_0 = 2\pi f t_0$$

where t_0 designates a constant, indicating the delay. Fig. 1 shows the attenuation and phase of a distortionless system.

Though a constant attenuation and delay do not give rise to distortion, they affect the transmission considerably. The attenuation determines the message power-output and, in telephonic transmission, the volume in the receiver. If the attenuation is too high, the random disturbances in the transmission path and the external noise reduce the intelligibility of the message. This implies the fixing of limiting values for the transmission equivalent of communication systems, the value for telephone transmission systems being about 30 decibels.

The delay also is of importance, though only for very long trunk-cable circuits. In a dialogue, the answer to a question does not arrive until after at least double the delay. If the propagation time is very long (about 1 second) considerable difficulties are encountered in carrying on a conversation. A maximum value of $\frac{1}{4}$ sec. for long-distance telephony has therefore been agreed upon by the Comité Consultatif International. This is important from the point of view of the dimensioning of the world's traffic line systems, designed to encircle the earth by means of a few meshes.

If the conditions for a distortionless system are not fulfilled, distortion arises during the transmission. Three departures from these conditions are possible:—

(*a*) The attenuation α has a different value for different frequencies.

(*b*) The phase difference β does not increase proportionally with frequency.

(*c*) The quantities α and β are not independent of the voltage and current amplitudes.

The first two types are linear distortions, i.e. amplitude distortion and phase distortion, whereas the third is spoken of as " non-linear distortion."

Amplitude Distortion.

The most important form of amplitude distortion is due to the restriction of the message frequency-range to the frequency range of the transmission system. The spectrum of a message contains, strictly speaking, all the frequencies between zero and infinity. Hence if the transmission system is effective only within the range of frequencies f_1 to f_2, the shape of the message is altered. The message must then be completed by guessing, and this means a reduction in intelligibility. In telephone systems a transmission range of at least 300 to 2 400 cycles per sec. has been agreed upon.

If sinusoidal signals are suddenly started, the limitation of frequencies to a definite range gives rise to transients. Fig. 2 (see Plate 1, facing page 780) shows, for instance, the building-up phenomenon through band-pass filters of a given frequency range $(f_2 - f_1)$. The transient is due to the absence of the components which lie outside the range f_1 to f_2. For relatively narrow band widths, e.g. those used in telegraphy, this consideration leads to the simple law:—

$$\text{Building-up period} \times \text{band width} = 1,$$

or

$$T = \frac{1}{f_2 - f_1}$$

Hence the keying speed is limited by the finite band width, and the rate of communication is proportional to the band width.* In such systems the energy dies out in oscillations having the border frequencies. Fig. 3

* K. KÜPFMÜLLER: " Transient Phenomena in Wave Filters," *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 141.

(Plate 1) shows that, on breaking a signal of 125 cycles per sec. in a programme line, the energy dies out in oscillations of 43 cycles per sec., the lower border frequency of this type of line. These results may be deduced from Fourier's integral and apply to an a.c. signal started suddenly. For a d.c. signal also the

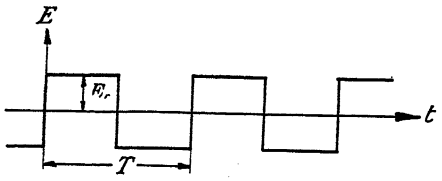


FIG. 4.—Rectangular wave.

building-up period can be calculated in a simple manner as follows:—

The Fourier series of the rectangular curve shown in Fig. 4 may be written

$$E = \frac{4E_0}{\pi}(\sin \omega_0 t + \tfrac{1}{3}\sin 3\omega_0 t + \tfrac{1}{5}\sin 5\omega_0 t + \ldots)$$

The greater the number of terms of this series taken into account, the more closely is the rectangular curve approximated. Fig. 5 shows the curve obtained by taking into account only the first three component oscillations; on the basis of this representation we may

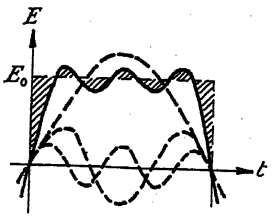


FIG. 5.—Oscillatory components of a rectangular wave.

speak of an " amplitude " spectrum. The curve shown in Fig. 6 is composed of various oscillations with definite frequencies and amplitudes.

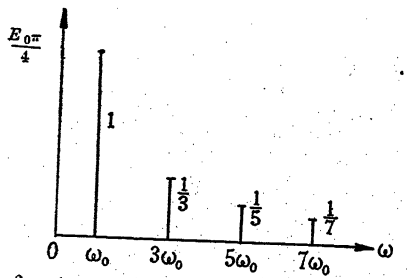


FIG. 6.—Amplitude spectrum of the oscillatory components.

Fig. 7 shows the rectangular curve shifted upwards in such a manner that time intervals in which the voltage is zero alternate with periods in which it has its full value. We have

$$E = E_0\left[\frac{1}{2} + \frac{2}{\pi}\sum_0^\infty \frac{\sin(2n+1)\omega_0 t}{2n+1}\right]$$

The greater one makes the period of the rectangular train, the lower the fundamental or basic frequency becomes, and the more closely the oscillatory components of the spectrum lie together. If the period is made infinite, as shown in Fig. 8, the periodic curve gives rise to the instantaneous change, and the summation becomes

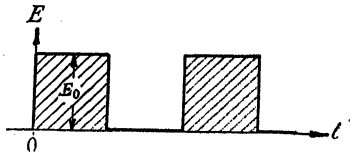


FIG. 7.—Rectangular curve with positive voltage ordinates only.

a process of integration. A single voltage step may be represented by

$$E = E_0\left[\frac{1}{2} + \frac{1}{\pi}\int_0^\infty \frac{\sin \omega t}{\omega} d\omega\right]$$

The amplitude spectrum has now become a continuous spectrum. In Fig. 9 we see that the amplitudes of the component oscillations decrease in inverse proportion to the frequency, or

$$a = \frac{E_0}{\pi}\cdot\frac{d\omega}{\omega}$$

An instantaneous change thus contains all the frequencies between zero and infinity.

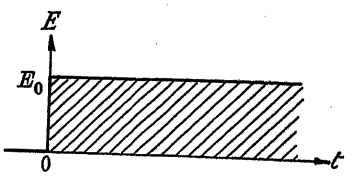


FIG. 8.—A single voltage step.

This representation enables one to determine in a simple manner how a restriction of the message frequency-range affects d.c. telegraphy. If the system transmits uniformly up to a definite frequency ω_0, all the components with lower frequencies must be summed up to give the magnitude/time function of the voltage at the end of the line. We have

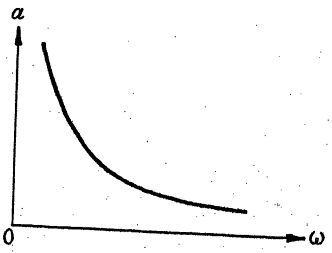


FIG. 9.—Amplitude spectrum of a single voltage step.

$$E = E_0 e^{-\alpha_0}\cdot\phi(t)$$

and

$$\phi(t) = \frac{1}{2} + \frac{1}{\pi}\int_0^{\omega_0} \frac{\sin \omega t}{\omega} d\omega$$

This function is shown in Fig. 10. The rise begins at a time t_0; the lower the cut-off frequency, i.e. the smaller the transmitted frequency range, the flatter the curve. If the building-up period T is defined according to the manner shown in Fig. 10, we obtain:—

$$T = \frac{\pi}{\omega_0} = \frac{1}{2f_0}$$

If, for instance, the system transmits all the frequencies between 0 and 50 cycles per sec. uniformly well,

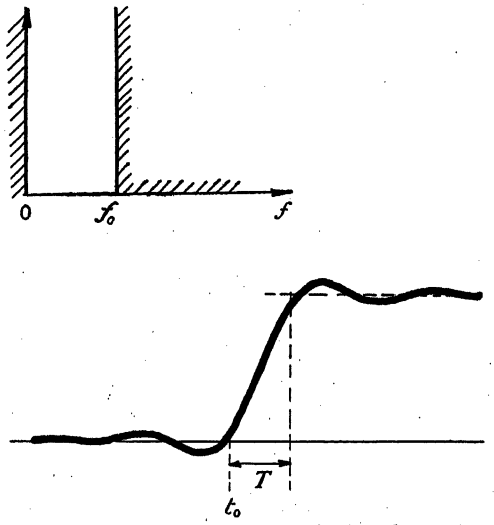


FIG. 10.—Transient curve of a single voltage step.

the building-up period of a suddenly-started d.c. signal is 1/100 sec. The maximum speed is in this case 100 signal elements per second (bauds). As shown in Fig. 2, the value of T for a suddenly-started carrier-current signal is $1/(f_2 - f_1)$ for a band width $(f_2 - f_1)$.

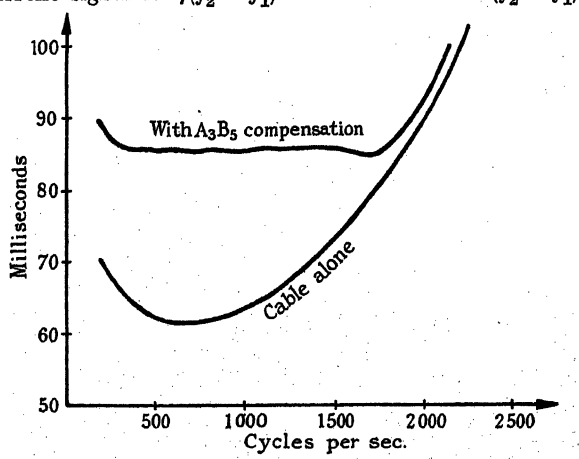


FIG. 11.—Propagation time of 1 000-km trunk cable.

This building-up period is twice that of a d.c. signal for the same band width. Therefore, for equal band widths, d.c. telegraphy permits of the transmission of double the amount of information conveyed by ordinary carrier-current telegraphy, provided the carrier frequency is located in the middle of the pass-band.

In telephony there is a method of carrier-current transmission known as " single side-band transmission."* It consists in shifting the carrier frequency to the border of the pass-band. As compared with double side-band transmission, only half the frequency range is required. This means that, for equal speeds of communication, the frequency range used for a carrier-current transmission need not be larger than that of an ordinary low-frequency transmission, a fact which is naturally of great importance from the point of view of the multiple utilization of lines.

Phase Distortion.

In a system with only phase distortion, no components are lacking in the message, but owing to the differences in delay of the various components the magnitude/time function of the message is altered. The ideal co-ordination has in part been lost, and this means a loss in intelligibility. As a measure of the action of phase distortion on the transmission of signals, use may be

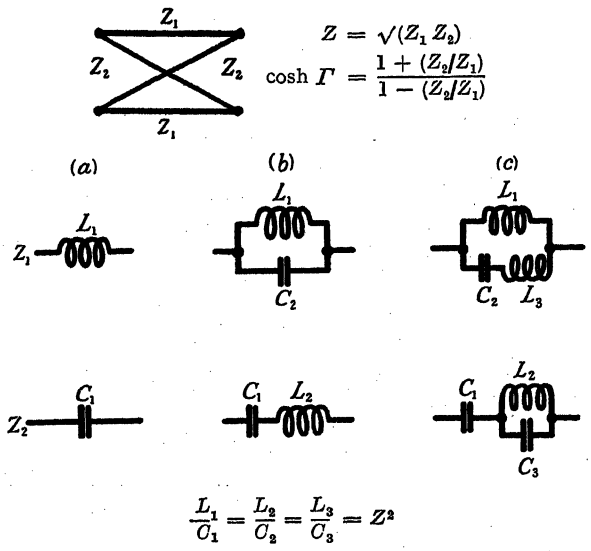


FIG. 14.—Phase-compensation networks.

made of the frequency response $d\beta/d\omega$, which has the dimensions of a time. Thus $t = d\beta/d\omega$. If $\beta = \omega t_0$, we obtain $t = t_0$, i.e. the delay is the same for all frequencies. In general, $d\beta/d\omega$ is dependent on frequency. Fig. 11 shows, for instance, the delay of a medium-heavy loaded trunk cable 1 000 km in length. The rise below is caused by repeaters and that above by loading coils.

A signal applied at a time $t = 0$ at the input of the system is perceived at the output at the earliest by a time corresponding to the smallest delay $d\beta/d\omega$. The signal approximately attains the steady state at the end of the system after a time $t = d\beta/d\omega$, where t is the delay of the signal frequency itself.†

Fig. 12 (Plate 2) shows the transient phenomenon in long coil-loaded circuits at 1 000 and 2 000 cycles per sec. The building-up period is approximately equal to the

* E. H. COLPITTS and O. B. BLACKWELL: " Carrier-Current Telephony and Telegraphy," *Transactions of the American I.E.E.*, 1921, vol. 40, p. 205.

† K. KÜPFMÜLLER and H. F. MAYER: " Transients in Periodically Loaded Lines and their Reduction by Compensating Networks," *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1926, vol. 5, p. 51; also J. R. CARSON: " The Building-Up of Sinusoidal Currents in Long Periodically Loaded Lines," *Bell System Technical Journal*, 1924, vol. 3, p. 558.

difference between $d\beta/d\omega$ for the signal frequency and the smallest value of $d\beta/d\omega$.

The difference in delay may become so great as to cause short signals, consisting of two frequencies, to appear resolved at the end. Fig. 13 (Plate 3) shows two frequencies transmitted over a distance of 3 000 km. Phase distortion can be eliminated in practice by the addition of phase equalizers, which consist of networks designed to make $d\beta/d\omega$ constant within the frequency range to be transmitted.

Fig. 14 shows different forms of such phase-compensating networks.

Fig. 15 (Plate 3) shows the transmission of two frequencies over a distance of 1 800 km, and Fig. 16 (Plate 4) illustrates picture transmission over different cable lengths without and with phase equalization.

Another method of keeping phase distortion within desirable limits consists in the light loading of long cable circuits. Phase equalizers are likely to be most extensively used on very long trunk lines, picture-transmission lines (which are very sensitive to phase distortion), and long programme lines.

Impedance.

A special form of amplitude and phase distortion is present if the parts constituting the system and the terminal apparatus are not adapted to one another. For example, Fig. 17 shows how a distortionless line, if terminated by distortionless impedances which are not equal to the characteristic impedance of the line, can impart distortion to the complete system. This type of distortion manifests itself not only in a reduction in efficiency (additional attenuation) and phase distortion, but also in echo effects. Echoes in communication systems produce widely different types of disturbances. Internal reflection in 2-wire circuits, for instance, limits the length of such lines. In the case of multiple lines the reflected currents become the source of objectionable near-end and far-end cross-talk. Special measures must be adopted in order to eliminate these effects. To keep the internal reflections small, severe demands are made on the uniformity of the lines and their loads, and on repeaters. Strict adaptation is also necessary for the terminal impedances. In cases where echo effects cannot be avoided (as, for instance, in 4-wire circuits) provision must be made for echo suppressors in order to eliminate echoes.*

The law of adaptation is presumably one of the oldest rules of the transmission art, and it plays an important part in all the inherent problems.

Non-Linear Distortions.

The disturbing effect of non-linear distortion consists in the occurrence of frequencies which were not present in the frequency spectrum of the original signal. The tones due to non-linear distortion act as a noise which interferes with the message. This noise may become more disturbing if it does not reach the receiver simultaneously with the message, which is the case, for instance, in non-linear systems with phase distortion.

* A. B. Clark and R. C. Mathes: "Echo Suppressors for Long Telephone Circuits," *Transactions of the American I.E.E.*, 1925, vol. 44, p. 481; also H. F. Mayer: "Echo Suppressors for Long Telephone Lines," *Elektrotechnische Zeitschrift*, 1926, vol. 47, p. 1379.

Non-linearity in lines is chiefly due to the amplifier valves [the 3/2 power law involves frequencies 2ω or $(\omega_1 \pm \omega_2)$] and to the iron-core coils [hysteresis involves frequencies 3ω or $(2\omega_1 \pm \omega_2)$ and $(\omega_1 \pm 2\omega_2)$] as shown in Fig. 18. In the general case non-linear interference is a complicated phenomenon, since interference tones occur at very different points—say, in each iron-core coil and each repeater—and finally combine to

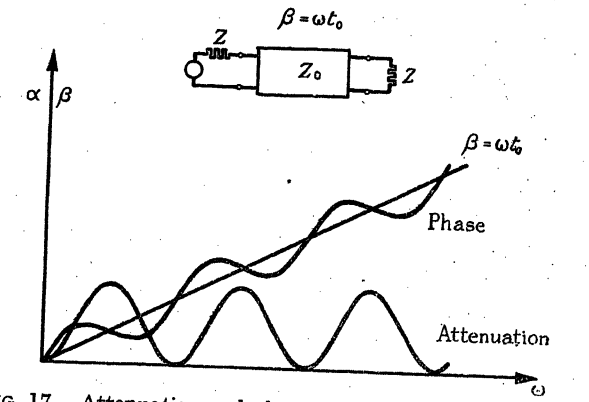


Fig. 17.—Attenuation and phase of homogeneous line in the case of unmatched impedances.

give an observable interference spectrum at the output. Fortunately, the effect of non-linear distortion on articulation is in general small. It is possible to avoid non-linear interference to a large extent by using suitably constructed repeaters and special material for the cores of loading coils. Much research work has been and is still being done in this domain.

Non-linearity is particularly undesirable if several

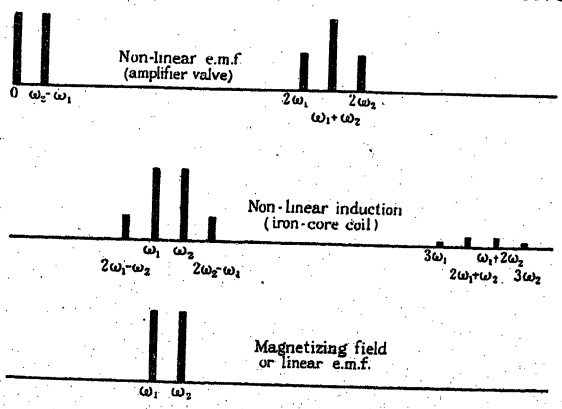


Fig. 18.—Interference tone spectrum due to amplifier valve and iron-core coil.

communication channels are to be operated on the same metallic circuit. In this case an interaction can be produced by non-linearity, which must be eliminated by means of special magnetic material and special dimensions of repeaters and terminal equipments. There are several possible ways of defining the different effects of non-linearity. One of these is by means of the "Klirrfactor," which indicates the ratio between the R.M.S. values of a fundamental and its overtones.

To face page 780.

Plate 1.

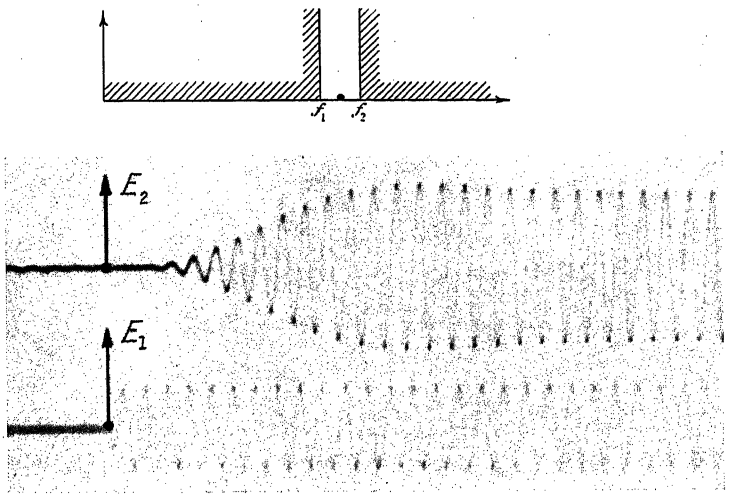


FIG. 2.—Building-up phenomenon through band-pass filter.

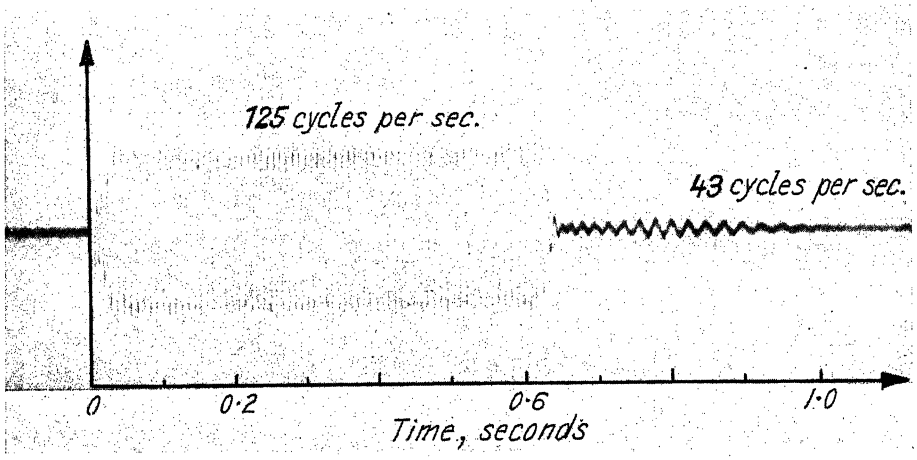


FIG. 3.—Decay of energy at lower border frequency of programme line.

Plate 2.

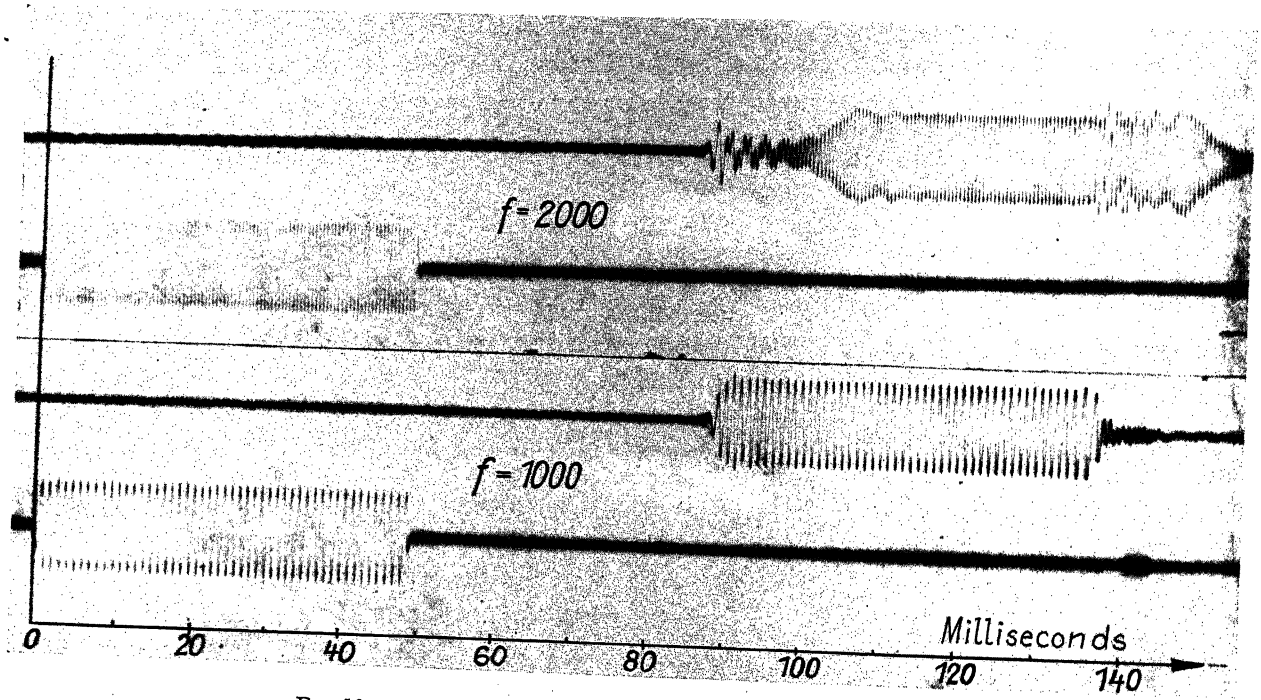


FIG. 12.—Transients in medium-heavy loaded cable 1 400 km long.

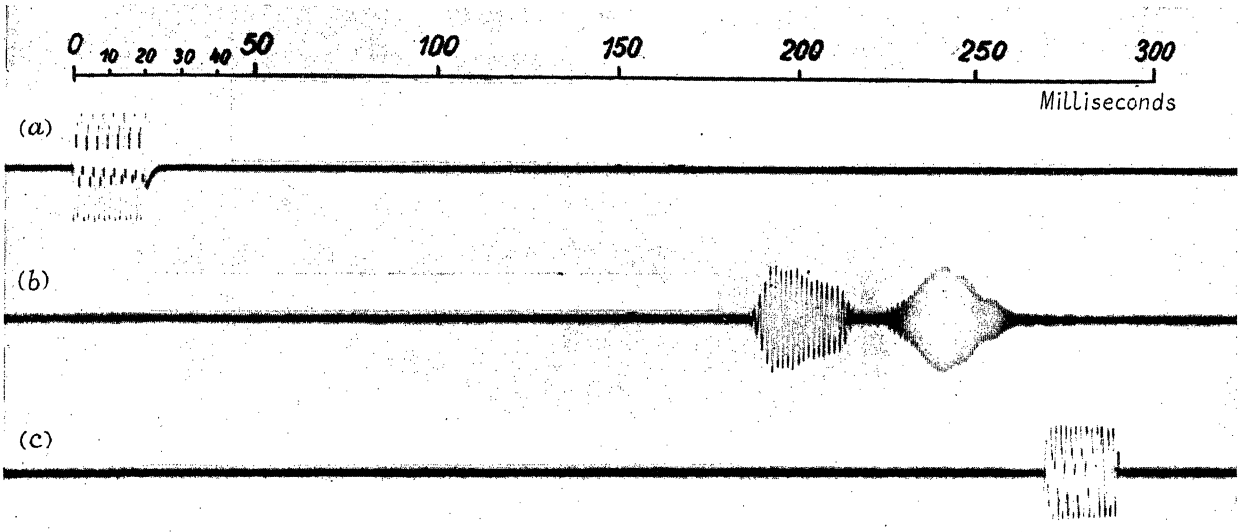


FIG. 13.—Effect of phase compensation.

(*a*) Frequencies of 700 and 1 650 cycles per sec. at input to 3 000 km of medium-heavy loaded cable.
(*b*) Output without phase compensation.
(*c*) Output with phase compensation.

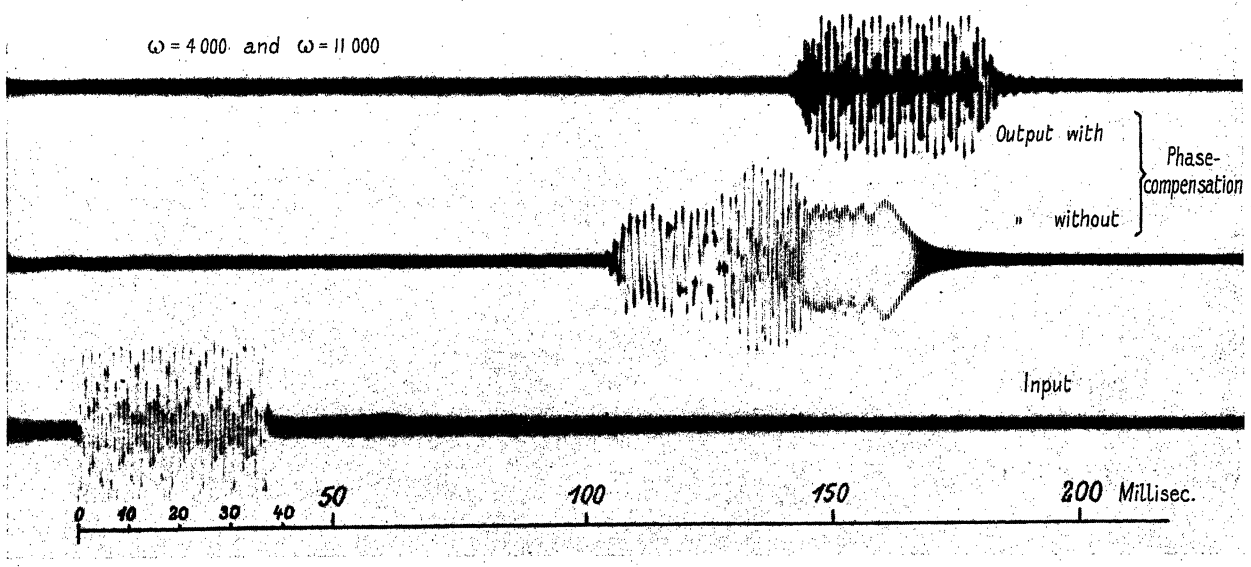


FIG. 15.—Effect of phase compensation on medium-heavy loaded cable 1 800 km long.

Plate 4.

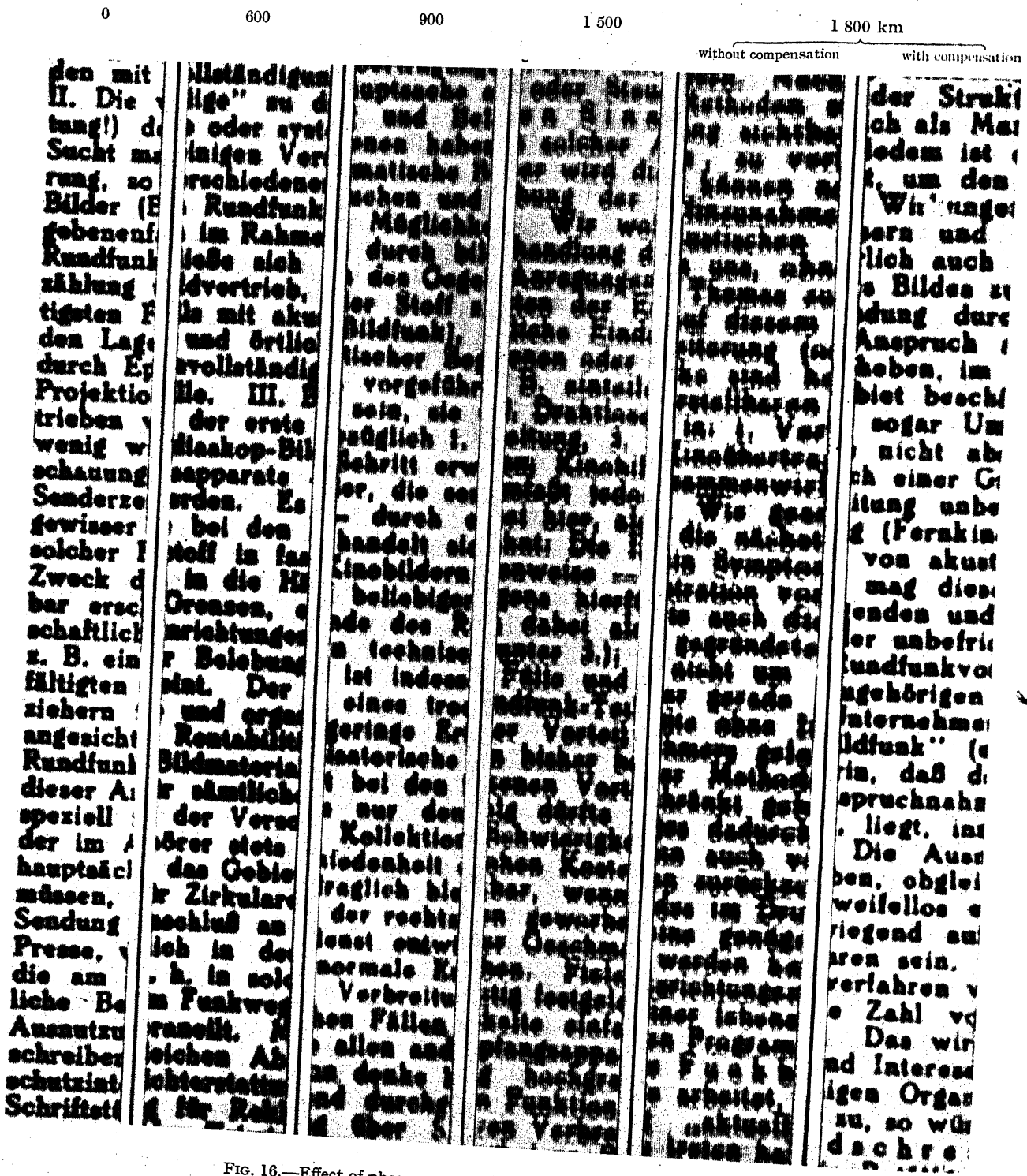


FIG. 16.—Effect of phase compensation on picture transmission.

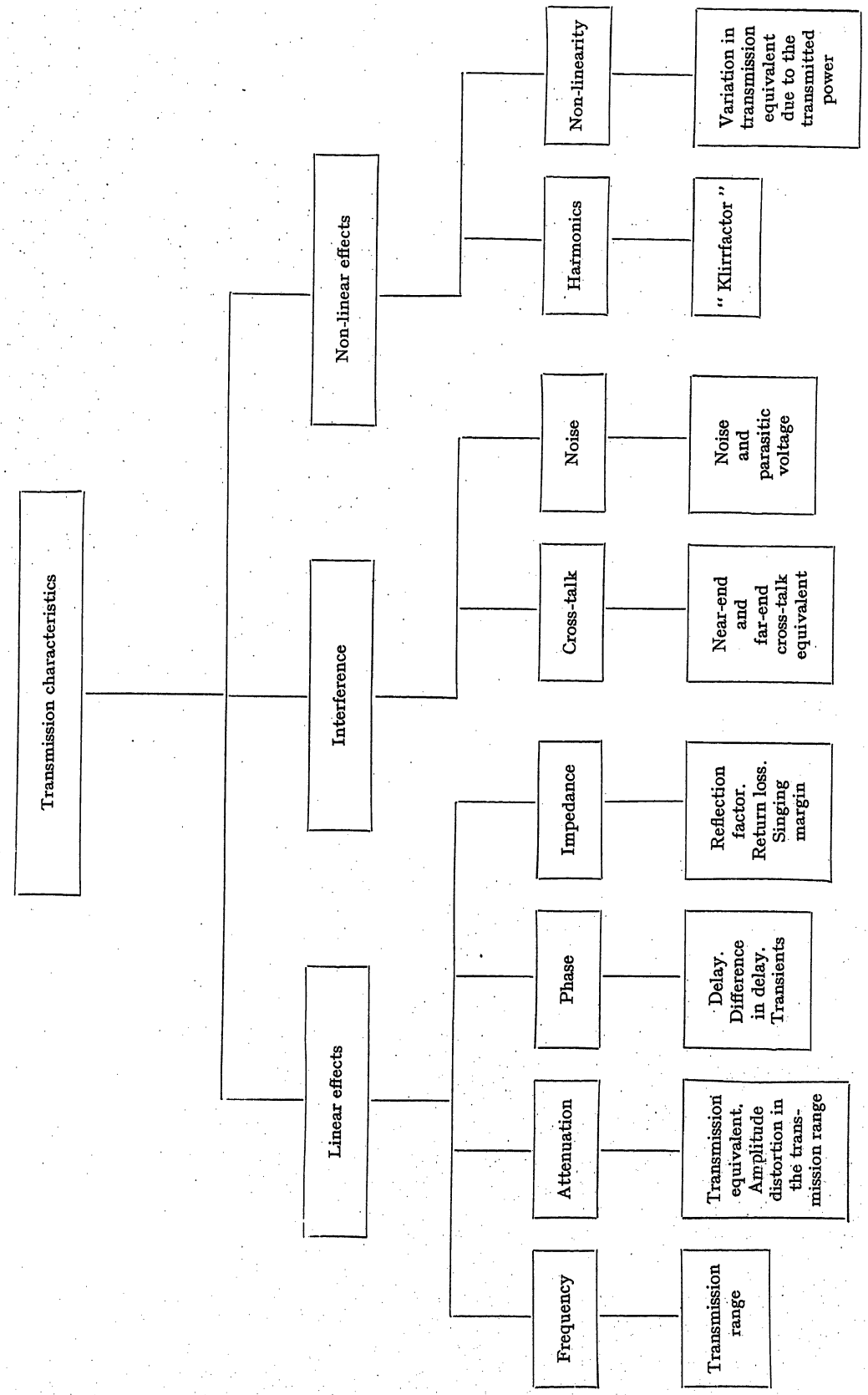


TABLE 1.

Transmission Characteristics.

Interference and Cross-talk.

Another source of such disturbances as affect the transmission of signals is interference due to power plants and cross-talk. Cross-talk, in particular, is apt to be disturbing because it is perceptible also in the pauses. If several lines of equal message frequency-ranges are operated alongside one another, interference arises from cross-talk which, under certain conditions, may be considerably increased by reflection at the ends. Much attention had therefore to be paid to these matters before it was possible to multiplex lines.

Table 1 shows the principal transmission characteristics in the form of a "pedigree."* For each of these characteristics limits must be fixed which naturally depend on the nature of the information to be transmitted. Table 2 gives a rough idea of the limits regarded as permissible in practice for some of the factors impairing transmission.

The demands which are to be made on a satisfactory transmission are independent of the type of transmission link employed; it is immaterial whether the transmission is effected over an aerial line, a cable, or with the aid of a carrier wave through the ether. Mention has therefore not been made of coil spacing, conductor gauge, capacitance of lines, and spacing of repeater stations. Many systems may be devised which meet the requirements set out in Table 2. In addition to the cable systems recommended by the C.C.I., others which seem to be better adapted to local communication needs have been used successfully, e.g. those recently set up in Holland. The question therefore arises whether the C.C.I. should not restrict its work in the future to the determination of electric and magnetic values.

TABLE 2.

Transmission characteristic	Telephony	Programme transmission	Telegraphy with start-stop	Picture transmission on lines
Transmission range, cycles per sec.	300 to 2 400	50 to 6 400	0 to 24	750 to 1 850
Variation in attenuation, decibels	± 6	± 3	± 3	± 4
Difference in delay, milliseconds	30	5*	20	1·0
Noise voltage as a fraction of the maximum transmission voltage	1/200	1/1 000	1/20	1/50
Maximum delay, milliseconds	250	—	—	—

* In the most important transmission range.

MULTIPLE UTILIZATION OF LINES AND OF WIRELESS CHANNELS.

The considerations presented in the first part of this paper have not only been the basis of rules for the development of ordinary telegraphy and telephony, but have also been of fundamental importance in the development of the equipments required for the multiple utilization of communication systems, one of the most striking features of modern communication engineering. This section will deal with some new developments in this direction, viz. 2-band telephony and the multiple utilization of a wireless wave.

* A similar pedigree may be found in Document 33 of the C.C.I., Paris, 1931.

A method of multiplexing aerial lines by means of carrier telephone systems has been in use for some time past. The development of carrier-current telephony began in the United States and Germany during the War,* and the system has now attained a high technical standard. Fig. 19 shows a pole-line design recently put into service in the U.S.A. Of 20 pairs of conductors, 16 carry 3 high-frequency channels each, in addition to the low-frequency communication circuits, and the other 4 pairs are equipped with 10 telegraph channels each. 20 pairs of wires thus result in 70 telephone and 80 telegraph circuits.

Multi-channel voice-frequency telegraphy over telephone cables had been developed by about the same time as the above-mentioned carrier telephone systems.† It permits of conveying from 6 to 12 telegraphic messages within the frequency range from about 400 to 2 000 cycles per sec., i.e. within the normal voice frequency, range of trunk-cable circuits. For measuring and signalling purposes, systems with 18 channels have even been developed. While the technical standard of carrier telephone systems on aerial lines and of carrier telegraph systems on cables is very high, the multiple utilization of cables for telephonic purposes has only recently become important.

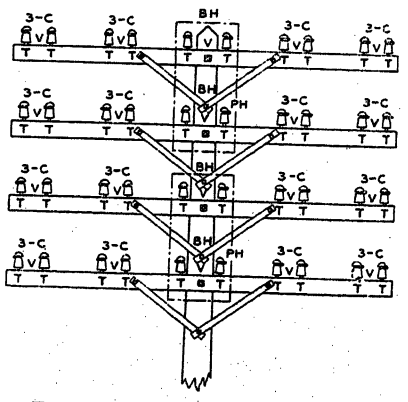


FIG. 19.—Pole-line configuration.

* F. B. JEWETT: "Multiplex Telephony and Telegraphy," *Telephone Engineer*, 1919, vol. 21, p. 53; also H. FASSBENDER and E. HABANN: "High-Frequency Multiplex Telephony and Telegraphy through Wires," *Jahrbuch der drahtlosen Telegraphie und Telephonie*, 1919, vol. 14, p. 451.

† F. LÜSCHEN: "Voice-Frequency Telegraphy," *Elektrotechnische Zeitschrift*, 1923, vol. 44, pp. 1, 28; also B. P. HAMILTON, N. NYQUIST, M. B. LONG, and W. A. PHELPS: "Voice-Frequency Carrier Telegraph System for Cables," *Transactions of the American I.E.E.*, 1925, vol. 44, p. 327.

According to a paper by A. B. Clark,* the U.S.A. contemplate the use of carrier-current systems on unloaded or very lightly loaded trunk cables with a high velocity of propagation. This may prove to be a way of obtaining circuits having a propagation velocity which is also sufficient for the longest trunk-cable communications, without sacrificing too much of their economy.

There are good reasons why the multiplexing of telephone-cable circuits is only now being seriously contemplated. At first, the normal voice-frequency utilization of cables involved a series of problems the solution of which entirely absorbed the attention of telephone engineers. Mention may be made of the successful efforts to solve such problems as amplitude distortion, phase distortion, echo effects, and non-linear distortion. Cables and repeaters had to be brought to a high standard of efficiency in order to secure reliable transmission of information over very long trunk lines. As a great number of conductors can be placed readily and economically in a land cable, the use of complicated terminal equipments such as are required for the multiple utilization of such lines did not appear justified.

The conditions are quite different so far as submarine-cable systems are concerned. The costs per km for a

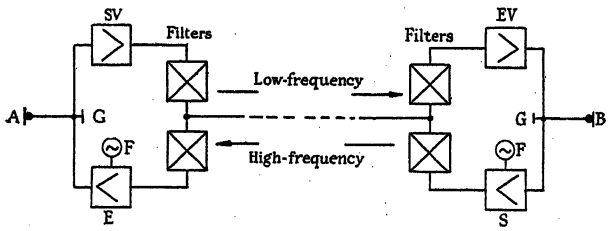


FIG. 20.—Schematic diagram of 2-band telephony.

pair of wires are here considerably higher and, in addition, greater distances must frequently be bridged without using through-line repeaters. Hence it was in connection with submarine cables that multiple utilization for telephonic purposes was first carried into effect, not only in unloaded single-wire cables but also in coil-loaded cables of many wires. Examples of the first type of cable are the Teneriffe–Grand Canary† and the paragutta cable from Key West to Havana.‡

Two-Band Telephone Systems.

The multiple utilization of coil-loaded submarine cables has recently been successfully achieved by means of the 2-band telephone system,§ which employs two frequency bands for a conversation over a metallic circuit. The schematic diagram of a 2-band system is given in Fig. 20.

Let two subscribers A and B be connected by a pair of wires. An increase in the length of the line, and consequently in the line attenuation, necessitates the use of 2-wire repeaters. For reasons of stability, however, 2-wire repeaters cannot be used when the length exceeds a certain limit, and in such cases it is necessary to add another pair of wires, i.e. to make use of 4-wire operation. In a 2-band system the required separation of the two directions of speech is obtained by providing a second channel on the same line, in addition to the normal voice-frequency channel. It is thus possible to save the expense of a second line. Subscriber A (Fig. 20) transmits speech over the terminating set G, the voice-frequency amplifier SV, the line, and the voice-frequency amplifier EV, to the subscriber B. The speech currents of the subscriber B are superimposed in the transmitter S on a carrier frequency f, flow over the carrier channel of the line circuit, thence to the receiver E, and, after being rectified and amplified, reach the receiver A as voice frequency. The separation of the two directions of speech at the two extremities of the circuit is achieved by means of filters. The width of the channels, as well as the selection of a carrier, are determined by the frequency band to be transmitted. Fig. 21

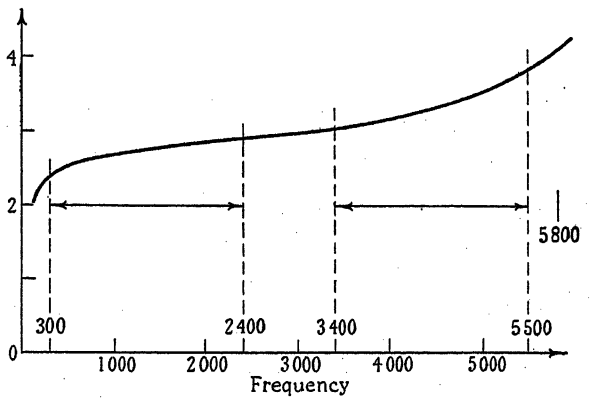


FIG. 21.—Allocation of frequencies in 2-band telephony.

shows a convenient frequency allocation designed for use in the fourth coil-loaded submarine cable between Germany and Sweden. This cable is 160 km in length. At the upper border frequency of 5 500 cycles per sec. it has a maximum attenuation of 44 decibels. The cable contains 42 quads, which permit of the setting up of 84 complete 2-band circuits.

In the 2-band system it is essential that the bands for the two directions of speech involved in a conversation should be transmitted over the same line circuit. Therefore non-linear effects produced by the loading material of the cable do not give rise to intermodulation, but only to echo effects. In case of need, echo effects can easily be eliminated by means of echo suppressors; such effects, however, have not as yet been observed in the short 2-band systems actually in use.

As may be seen from Fig. 21, the frequencies of the two channels are quite low, so that a 2-band system may be regarded as a low-frequency system, and in fact the art of 2-band telephony differs in no way from that of ordinary telephony. Therefore 2-band communications have attained a very high degree of technical perfection and reliability.

As to the economic aspect of 2-band telephony, the conditions are, of course, very favourable if existing cables can be adapted for 2-band operation. This is

* A. B. CLARK: "Recent Developments in Long Distance Cables," Bell Telephone Co. Monograph No. B.486, May 1930.
† T. CALDWELL: *Electrical Communication*, 1931, vol. 9, p. 222; also K. E. LATIMER and J. R. VEZEY: p. 226.
‡ J. J. GILBERT: *Bell Laboratories Record*, 1931, vol. 9, p. 412.
§ H. F MAYER: "Two-Band Telephony," *Telegraphen-und Fernsprech-Technik*, 1929, vol. 18, p. 312.

possible in the case of unloaded cables, and of continuously loaded or periodically light-loaded cables of medium length having an attenuation not exceeding

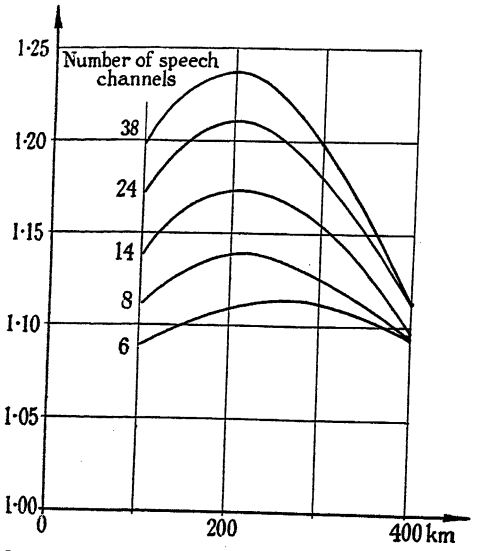


FIG. 22.—Relative costs of 4-wire systems and 2-band systems (300 to 2 400 cycles per sec.). Overall attenuation = 52 decibels (6 népers).

50 to 70 decibels at frequencies up to about 5 500 cycles per sec. In such cables it is possible to duplicate the number of speaking circuits at a relatively low cost. To find out to what extent economies can be effected

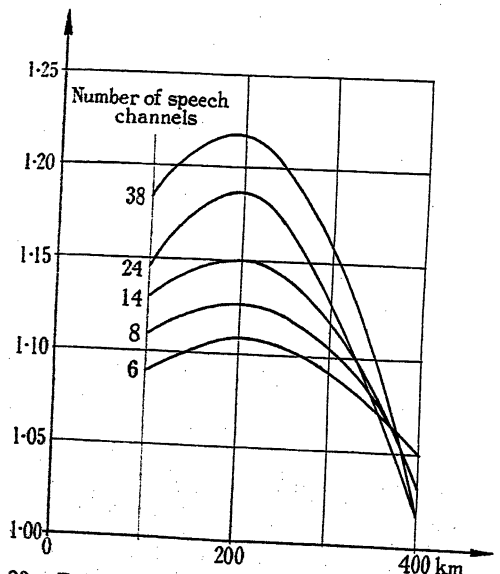


FIG. 23.—Relative costs of 4-wire systems and 2-band systems (300 to 3 000 cycles per sec.).

in new plants, as compared with 4-wire operation, each case must be examined on its own merits.

Such economy computations have been carried out in numerous cases, and some of the results are shown in figs. 22 and 23. A 2-band cable and a 4-wire cable are compared under the following conditions. The cables are of equal attenuation and have frequency ranges of equal widths, their cut-off frequencies being approximately in the ratio 2 : 1. The transients in 2-band channels are not of greater magnitude than those inherent in the 4-wire frequency range. The economies effected by the 2-band system for the important range from 100 to 300 km amount to 10 to 25 per cent. In addition, the 2-band system offers the advantage that its delay is about one-half that of the 4-wire cable

Hence 2-band operation may offer advantages from both the electrical and the economic aspect, not only for the extension of existing plants but also for new plants.

Another field of application of the 2-band system is in connection with very long deep-sea cables, which, for mechanical reasons, can be set up only as continuously-loaded paragutta cables having one conductor and a concentric earthed return. Such a cable permits of obtaining only one circuit in 2-wire operation. For reasons of stability, use must be made of a flip-flap device, which is, of course, no ideal solution. On using the 2-band system, the flip-flap device can be dispensed with up to certain lengths. Thus one obtains a circuit which, with respect to stability, is equivalent to a 4-wire circuit. This fact will in future play an important part in the design of long deep-sea cables.

INCREASE OF THE ECONOMY AND RELIABILITY OF SHORT-WAVE CONNECTIONS.

The long-distance wireless communication service was until quite recently limited exclusively to telegraphic operation with morse signals and audible or visual reception. The first telephonic communication system was the long-wave connection England–America, and this was followed by a series of short-wave connections between various countries.

The communication systems of the various continents could in this way be coupled with one another. The work recently carried out has aimed in the first place at improving the economy and reliability of such transcontinental channels. Increasing use is being made of facilities developed in the voice-frequency art, on the basis of the multiple utilization of these channels and the transition from the morse system to the operation of type printers.

The question of economy is particularly vital for telephone channels, because it sometimes does not appear to be justifiable to put a special radio transmitter and receiver into service solely for the telephone, in view of the fact that high charges prevent heavy traffic and low charges do not cover the cost of service. The problem is complicated by the difficulty that where the countries are in different geographical longitudes, a uniform loading of the lines throughout many hours, which would involve a lowering of fees, is impossible since the business hours of interconnected countries overlap one another only for a short time. It would also be difficult to stop the existing telegraph lines during these hours, because the telegraph and telephone traffics naturally increase simultaneously. It is obvious that here, in particular, one should try to apply the multiple utilization of carrier systems simultaneously to the telephone and the telegraph, a view which is supported by the fact that for

short-wave lines an excess of received energy is often available at the hours of favourable working conditions. Tests of this nature have already been carried out in various countries, e.g. between England and Canada by Marconi.

So far as Germany is concerned, a system of simultaneous telephony and telegraphy has been tested between Berlin and Buenos Aires.* It was designed to transmit speech and two telegraphic messages simultaneously. An important feature of this system is that multiple utilization is achieved only by adding supplementary normal low-frequency apparatus to an existing carrier-telephone circuit. The speech frequencies are thereby led to the transmitter in the normal manner. The transmission of telegraphic messages is effected as follows:—

The marks and the spaces each have imparted to them a low frequency, and the marking and spacing frequencies only differ by about 100 cycles per sec. In practice, a valve generator tuned to one frequency is, by the addition of a condenser, changed over to the other frequency. At the receiving end, the marks and spaces, after demodulation, are discriminated and led to a rectifier which supplies two separate windings of the receiving relay in opposite directions. If both rectifiers are energized simultaneously, which may occur in the case of atmospherics, their actions on the relay neutralize each other, whereas the working of only one rectifier causes the reversal of the relay armature. In this way some amount of protection against additional signals (fills) may be obtained.

Another advantage of this system consists in the exact fading control. As contrasted with the normal method of keying the message transmitter, a signal frequency is always available at the receiving end and can be used for automatic amplitude control. Since it is not necessary to give the control a long hang-over for bridging the spaces the fadings can be followed up rapidly, regardless of the keying speed.

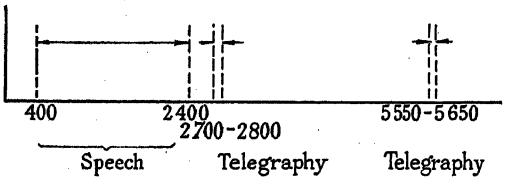


FIG. 24.—Allocation of frequencies for simultaneous telephony and telegraphy on Berlin–Buenos Aires link.

In the actual multi-channel system use was made of two such telegraph channels, which could either be operated separately or combined in parallel. The control device for one channel was thereby used to deal with the speech amplitudes also. An accurate control cannot be obtained in this manner, since the action of the selective fadings on the amplitudes of speech frequencies differs from that on the controlling telegraph frequencies. Tests have, however, shown that such a control has, on an average, a compensating effect.

Fig. 24 shows the frequency allocation for the various channels. The talking channel comprises the frequencies of from 400 to 2 400 cycles per sec. The first telegraph channel contains the frequencies of from 2 700 to 2 800 cycles per sec., and the second the frequencies of from 5 550 to 5 650 cycles per sec. With this allocation of the telegraph channels, the talking channel remains practically free from interference tones.

Fig. 25 shows the schematic diagram of the plant. Speech currents coming from a trunk line or microphone are restricted by the filters K_1 to the prescribed range. Behind K_1 the first component channel (2 700 to 2 800 cycles per sec.) is added. G_2 is a valve generator, the frequency of which is altered for marks and spaces. Filter K_4 restricts the channel to the range imposed by the keying speed. Behind the input amplifier VV, the second telegraph channel (5 550 to 5 650 cycles per sec.) is added. Both channels, if combined, are keyed in parallel. The transmitter S is normally modulated by the frequency mixture of speech and telegraph signals, the resultant amplitude being controlled by a modulation meter.

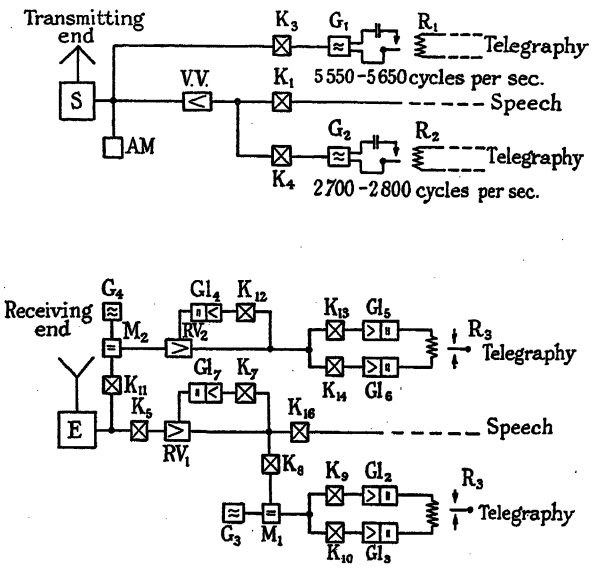


FIG. 25.—Schematic diagram of multiplexing system of Berlin–Buenos Aires link.

At the receiving end the receiver E picks up the mixture of speech and telegraph signals. After demodulation, the first separation is carried out in such a manner that the frequencies 2 700 to 2 800 cycles per sec. and the voice frequencies pass through a filter K_5, whereas the frequencies 5 550 to 5 650 cycles per sec. are rejected and make their way through the filter K_{11}. Speech and the first telegraph channel are controlled in the common regulation amplifier through the filter K_7 and the input amplifier-detector Gl_7. Only the voice currents reach the subscriber through the filter K_{16}. The signal frequencies, after having passed through K_{16}, are stepped down to the frequencies 250 to 350 cycles per sec. with the aid of the local oscillator G_3 and the modulator M_1, so as to enable them to be separated reliably from one another by simple filters K_9 and K_{10}. The frequencies actuate the rectifiers Gl_2 and Gl_3, to which a winding of relay R_3 is connected. Thus the connection of the

* D. Thierbach: "Simultaneous Telegraphy and Telephony on Short-Wave Communication Systems," *Telefunken-Zeitung*, March 1932.

windings is so designed as to cause the two rectifiers to counteract each other.

The second channel is designed in much the same manner; the frequency transformation is achieved by the local oscillator G_4 and modulator M_2; control is effected in the regulating amplifier RV_2, with the aid of the amplifier-detector Gl_4 and filter K_{12}. The marking and spacing frequencies are selected one from another by filters K_{13} and K_{14}, associated with the rectifiers Gl_5 and Gl_6 respectively, the latter being connected, for combined channels, in the same way to two windings of relay R_3. If the telegraph channels are operated separately, a special relay is, of course, assigned to each channel.

Practical tests were carried out on the radio link between Buenos Aires and Berlin with the assistance of the Transradio International in Buenos Aires, the German Post Office, and the Transradio A.G., Berlin. The transmitter was at Monte Grande, the receiver at Beelitz near Berlin. The tests with morse working and visual reception proved to be so successful as to enable commercial telephone and telegraph traffic to be carried over this system. The multiplex transmitter had a telephone output of 20 kW. Each of the two telegraph channels required 15 per cent of the maximum permissible amplitude, thus leaving 70 per cent for the speech channel. It may be of interest to add that another 20-kW transmitter keyed in the normal way for one telegram, gave more faults than did the multiplex system, though the available energy was in this case much smaller than for the normal telegraph transmitter.

A further series of tests was made to ascertain whether it is possible to abolish the morse system in short-wave operation and to substitute the type-printing apparatus, the use of which would represent an important advance. The demands thus made on the quality of the received signals are higher, however, since they are dealt with mechanically on being received and a machine has not the corrective capacity of an intelligent operator. For the tests Buenos Aires–Berlin, use was made of a teletype of standard construction. In this case also, the total number of faults was kept within permissible limits. The proportion of faults in the transmitted letters lay between 0·1 and 0·8 per cent, according to the inherent conditions. These and similar tests carried out in other places have evidenced that multiple utilization and printing-telegraph working can be achieved in practice when equipment suitable for short-wave channels is employed.

It must be admitted that the use of special systems involves practical difficulties. Morse operation has been adopted internationally, so that intercommunication is feasible between any two stations. This is not so as regards special systems, which, of course, can only be operated if both stations are equipped with the appropriate apparatus. After a definite solution of the technical problems has been arrived at, it will be necessary to come to an agreement upon these points.

Reverting to the important theorem given at the beginning of the paper in the form suggested by Hartley, this has been called by K. Küpfmüller the "time law of the communication art."* The law states that for each method of transmitting information the product of the transmission time for a letter and the width of the frequency range required is a constant independent of the transmission speed. In Table 3 the constant k is given for several types of communication systems.

TABLE 3.

Transmission time × band width = k

Means of transmission	Speed of transmission		Frequency band	Transmission time of a letter	k
	Letters per minute	Bauds	cycles per sec.	second	
Teletype, d.c.	400	48	24	0·15	3·5
Teletype, a.c.	400	48	48	0·15	7·0
High-speed Siemens d.c.	600	50	25	0·10	2·5
Quadruple Baudot d.c.	4 × 180	66	33	0·083	2·7
Submarine-cable telegraphy	300	20	10	0·20	1·9
Picture transmission	200	—	1 100	0·30	330
Telephony	750 to 1 500	—	2 000	0·04 to 0·08	80

The time law permits one to compare the efficiency of any new method of transmitting information with the known method. From the efficiency standpoint the teletype communication system is much better than the telephone system. On the other hand, it gives some hints as to the limits set to the development of communication engineering. An interesting question, for instance, is the one relating to the lower limit of the quantity k for a given number of signal elements. As regards the simplest code consisting of two signal elements only, the answer to this question results from the fact that the transmission of a signal involves at least one change of current. The frequency range must therefore be at least large enough to make the building-up period shorter than the duration of a complete signal. For a signal of 1/1 000 sec., for instance, we need a band width of at least 500 cycles per sec. We thus obtain for k the value $\frac{1}{2}$ as the lower limit for each type of communication system.

* K. KÜPFMÜLLER: "Transients in Telegraph and Telephone Engineering," *Teknisk Tidskrift*, 1931, Nos. 9 and 10.

A great number of European and American physicists and engineers have shared in the development of communication engineering, so that it is often difficult to state the origin of a new idea or an advance on previous practice. The author has therefore in general refrained from mentioning names in this brief résumé of the subject.

In conclusion, he desires to acknowledge his indebtedness to Miss E. Boysen for her assistance in translating the paper.

Discussion before The Institution, 7th April, 1932.

Col. Sir Thomas F. Purves: (After references to Dr. Lüschen's personal work in the field of electrical communications.) I am in sympathy with the author's desire that the C.C.I. should concentrate its attention increasingly upon specifying the electrical and magnetic qualities to be aimed at in the construction of lines in the international network, and should more and more leave the actual make-up of the lines to be settled by each nation in the way best suited to its own local conditions and developed practice. The procedure of the C.C.I. is not, however, open to much criticism in this respect. When its conferences started, many of the less-developed nations were very much in the dark as to the best available methods of constructing telephone equipment. I think that, in the conditions then existing, we did well to lay down specifications in a fairly detailed way. I freely admit that some of them were, even then, rather too rigid in the matter of ways and means, but they did not last long in that form. The tendency now is to recast the *avis* and the specifications of the C.C.I. more and more as purely performance specifications, and to supplement them by descriptions of various alternative systems that have been found successful in practice. The 2-band system of telephony, the subject of the second portion of the present paper, is a notable German development which has attracted widespread attention. Applied in the way the author describes—to the formation of up-and-down channels on a 2-wire submarine-cable circuit connected at each end with long 4-wire land circuits—it is an extremely pretty conception, and it is good to hear that it is meeting with great success. The British Post Office method of doing the same thing—by means of a 2- to 4-wire balance equipped with automatic stabilizers—also appears to be a good one, and it is perhaps even simpler and cheaper than the 2-band system for that purpose. I am somewhat intrigued by the author's friendly and familiar use of the decibel as a transmission unit. I should like to think that it is an indication that the decibel is now finding favour in Germany, but I rather fear that it is only a graceful compliment on the part of the author in the case of a paper written in English for delivery in London.

Mr. A. B. Hart: The paper brings to our notice the tremendous advances that have been made in the last 20 years. It is instructive to compare it with other papers written under somewhat similar circumstances (*a*) 20 years ago, and (*b*) 10 years ago. As regards (*a*), we may take as a criterion of the state of advancement in technical matters a series of papers presented to the Budapest Conference of Telegraph Engineers in 1908, and the Paris Conference of Telegraph and Telephone Engineers in 1910. I suggest as a criterion for (*b*) a document bearing the title "Long-Distance Telephony" which was prepared by the Reichspost Ministerium, Berlin, and presented to the first full meeting of the Comité Consultatif International at Paris in 1924. The papers of 1910 show that communication engineers were at that time chiefly concerned with the development of the various systems of operating communication channels. Transmission engineering had hardly emerged from the laboratory stage. The loading coil had just appeared; the telephone repeater was still a dream, and little mention was made of long-distance communication as an art. In 1924 it was stated: "For long-distance communications between international centres connected by cables, 2-wire circuits may be used if the attenuation does not exceed 75 standard miles of cable," i.e. talking over a loaded-cable 2-wire circuit is possible for a distance of 480 km (300 miles), and: "For longer distances one can in the actual state of technique utilize 4-wire circuits up to a distance of 1 000 miles." However, even at that time some telephone engineers had begun to foresee such difficulties as echoes and phase distortion in the way of satisfactory long-distance cable telephony, difficulties which are clearly explained in the present paper. Turning to the section which deals with the latest developments in communication systems, I think that the utilization of 2-band and carrier-current systems is of great importance to this country just now. Finally, I would express a little disappointment that the author makes no mention of television, which is surely one of the outstanding modern developments in the communication art.

Mr. H. H. Harrison: Two-band telephony has now reached a stage of development when it will require very careful investigation. In this connection I would refer to an article by Dr. K. O. Schmidt,* of the German Post Office, in which the comparative costs of 4-wire 2-band and 2-wire 2-band telephony for land cables are set out at great length. With regard to the combined telegraph and telephone system on the radio link between Berlin and Buenos Aires, I should be glad of further details of the method of duplexing. Is transmission one way effected on one channel and the other transmission on another channel? With regard to signal distortion on telegraph circuits employing either a cable or radio link, this can be very largely eliminated by means of regenerative repeaters. With the introduction of start-stop printers on long-distance links, however, we shall have to consider the possible signal distortion in the apparatus itself. It may be necessary to return to the early design of teleprinter in which provision was made for orientation of the receiving cams.

Mr. G. C. Marris: I am particularly interested in Figs. 4, 5, and 6, relating to the break-up of a square

* "On the Possibilities and Advantages of 2-Band Telephony over Land Telephone Cables," *Telegraphen-und Fernsprech-Technik*, 1932, vol. 21, p. 68.

wave into its odd harmonics, as such an analysis is the basis of a method we have now had in use for some time for the generation of sine waves. When certain difficulties had been overcome it proved an effective method of obtaining a large number of pure frequencies which were odd multiples of the fundamental. With regard to the remark on page 780 that " non-linearity in lines is chiefly due to the amplifier valves and to the iron-core coils," while this is true of the lines it might be emphasized that valves are only minor causes of distortion in the overall transmission, because the best commercial microphones introduce far more non-linear distortion. Repeater valves commonly produce some 3 per cent of harmonics at full load, but the full load is designed to take care of the peaks in speech wave-form. It is doubtful whether the distortion represented by 3 per cent of harmonics on such peaks has any effect on articulation; while on normal speech the percentage of harmonics is likely to be only about 0·2 per cent, that is, in absolute value, probably below audibility except on the longest repeatered lines. Table 3 might easily be misinterpreted, since there is an inference that a letter is a unit of information. That this is not so is clear when one remembers that the communication art does not restrict itself to transmitting the alphabet. Thus telephone speech, which transmits letters in the shortest time but with the largest value of k, transmits at the same time much additional information; some idea of the speaker's individuality is conveyed by the tone of the voice. It follows, therefore, that k is not a complete measure of the value of a channel. On page 779 the author just stops short of suggesting single side-band transmission for voice-frequency telegraphy. Does he consider that this is practicable or desirable?

Captain J. G. Hines: The band width at present regarded as necessary for the transmission of human speech is 2 400 cycles per sec.; does the author consider that this figure is likely to remain the standard? As the early phonograph with its ear-tubes gave way to the gramophone, and the headphones used in the early days of broadcasting have been replaced by the loud-speaker, so I think that in commercial telephone practice the hand telephone will in due course be abandoned in favour of the loud-speaking telephone in offices where there is only one telephone. An ordinary conversation over a line having a band width of 2 400 cycles per sec. is less intelligible when received on a good loud-speaker than by means of the ordinary ear telephone. Tests have indicated that in order to get equal intelligibility on a loud-speaker it is necessary to increase the frequency band of the transmission system One reason for this is that when a receiver is placed against the ear the mind is concentrated upon the sound entering that ear, and some of the higher frequencies—although faint—can be distinguished. There is also the fact that a hand telephone only allows one ear to listen to disturbing noises, the other being occupied by the receiver. When a loud-speaker is used the speech is merged with the other noises in the room, and therefore one does not focus so readily upon the particular sounds it is desired to listen to. The higher frequencies may be present in an attenuated form, but they cannot be heard. Towards the end of the paper the author states that from " the efficiency standpoint the teletype communication system is much better than the telephone system." This may be true if the number of words transmitted in a certain time is regarded as the test of efficiency. I am inclined to think, however, that the number of words transmitted in a certain time is not the true test of efficiency on a communication circuit. In communicating ideas, emphasis and inflection play a hardly less important part than the words used, and for this reason I think that printed characters will never be regarded as a satisfactory substitute for the voice. The teletype system cannot replace the telephone, although it may supplement the spoken word. The importance of emphasis and inflection is an additional reason why the voice which is received should be a faithful reproduction of the voice at the distant end. The ideal at which we have to aim, therefore, is to transmit all the frequencies present in the voice of the speaker; at present this ideal is not economically practicable. Anyone who has listened on a distortionless circuit, such as the standard transmission system, will appreciate how easily ideas can be communicated over it as compared with the best practicable form of commercial circuit. I wish to emphasize that we must not make too serious a raid on what we are inclined to call the " unwanted " portion of the frequency spectrum, as such a course may prevent us from obtaining the wide band of frequencies which will be necessary later on. With regard to the multiple utilization of lines, the Post Office has a cable between England and Holland that contains 8 telephone pairs, each of which is being used as a telephone circuit. On those 8 pairs 4 more circuits are superimposed, on those 4 there are superimposed 2 more, on those 2 there is superimposed one circuit, and finally all the circuits are connected in parallel with an earth return. Thus 16 telephone communication circuits are obtained with 16 wires. This did not exhaust the possibilities, it being found practicable to add 2 carrier-frequency telephone channels to the same cable. Arrangements are now being made to add 2 more carrier-frequency circuits, so that in all 20 telephone circuits will be working on 8 pairs of wires. The cable is continuously loaded and has a high cut-off frequency, with absence of " flutter." At the other end of the scale we have a single-wire cable from Guernsey to England, which we have adapted so as to enable it to carry a telephone circuit in addition to the telegraph circuit. This was done by inserting a special type of repeater with an echo-suppressor and a stabilizer. Intermediate between these examples, there is a circuit between London and Edinburgh which has a picture channel and 3 telegraph channels working simultaneously. The capabilities of the 2-band system have been under investigation by the British Post Office, but hitherto it has not been considered so advantageous as the systems mentioned above for the conditions under which cables have to be laid and maintained in the seas around Britain. It is quite possible, however, that circumstances favourable to its adoption may arise.

Mr. H. T. Werren: Table 1 includes two important transmission characteristics—interference and impedance (uniformity of impedance)—which are largely dependent on the skill of the cable manufacturer. Nearly five

years ago, at the C.C.I. meeting at Como, the present author stated that the maximum permissible repeater-section attenuation—a factor which controls the cost of the line—was dependent on the cross-talk in the cable. To-day we are installing cables in which the average cross-talk per repeater section is less than 40 millionths (88 decibels), and the maximum cross-talk between any two circuits in the cable does not exceed 100 millionths (80 decibels). This represents a considerable improvement. On page 782 the author refers to the multiple utilization of lines by multi-channel voice-frequency telegraphs and 2-band telephony, both of which result in considerable economy in line plant. I should like to point out, however, that the incorporation of many channels of communication in one cable necessitates special attention to the maintenance of the cable system, as the loss of a large number of channels through one cable fault would result in complete disorganization of traffic. In this connection it would seem that the British Post Office have rightly anticipated developments by installing star-quad cables, in which metallic circuits replace the phantom circuits of the older-type multiple-twin cable. In a phantom-loaded cable a low-insulation fault immediately puts all the phantom circuits out of action, on account of excessive cross-talk: this characteristic is not exhibited by star-quad cables. The Post Office policy of the more extensive use of 4-wire instead of 2-wire circuits also appears to be right, particularly in view of the possibilities of 2-band telephony. A cable fault which would quickly render a 2-wire circuit useless, would not put a 4-wire circuit out of operation. For example, in a recent case the insulation of a cable dropped to 3 000 ohms on account of a fault, but all the 4-wire circuits—including some used for broadcasting—continued to operate satisfactorily. With regard to Figs. 22 and 23, it is difficult to compare the relative costs of 4-wire and 2-band systems on account of fluctuations in the market prices of copper and lead. I should like to ask the author on what price basis the comparisons shown in Figs. 22 and 23 were made. The system of simultaneous telephony and telegraphy described on pages 785 and 786 is of great importance to this country. Whereas only a few years ago we were at the extreme end of the European communication system, to-day we are becoming the centre of a world system. This change not only affects the design of the system in this country, but it should also be of inestimable value to all those connected with industry.

Captain A. C. Timmis: The main application of the 2-band system is to long coil-loaded submarine cables such as those between Germany and Sweden. Some time ago I made a rough theoretical comparison, for a length of 100 miles, between two types of cable of the same size and weight, one containing a large number of conductors and using the 2-band system, the other with a smaller number of conductors (the same type of cable as the Anglo-Dutch referred to by Captain Hines) using phantoms, super-phantoms, and carrier circuits. I found that, ignoring any question of ease of repair, the cost per circuit of the latter type—giving with the carriers a total of 21 channels on the cable—was 20 or 25 per cent less than that of the former. The advantage of the 4-quad cable is due to the symmetrical arrangement, allowing the maximum number of super-phantoms. According to the author, another field of application for the 2-band system is to form a telephone channel on a long single-core submarine cable, such as that already referred to, between England and the Channel Islands. In this case, however, the frequency range of the cable is very limited (in fact, the attenuation rises to 55 decibels at 2 000 cycles per sec.) and it would obviously be impossible to obtain the range of about 5 500 cycles per sec. required for the 2-band system. We have succeeded in working it as a telephone circuit, however, by making very accurate balances and stabilizing the 4-wire circuit to which it is connected on the mainland. The stabilizer is a voice-operated device; it should not be confused with what the author describes as the " flip-flap " type of apparatus, which alternately switches on and off in either direction of transmission. The stabilizer has the advantage that it never switches off the amplification completely. When no one is talking on the circuit the amplification is reduced just sufficiently to prevent the circuit from " howling," and when conversation starts the amplification is automatically restored to normal in the direction required. The stabilizing system is, however, arranged to operate only at the higher frequencies where the ordinary means are not sufficient to maintain stability. The middle frequencies of speech are transmitted in the normal way, and there is practically no trouble from clipping of the initial speech sounds. The overall attenuation of the London–Guernsey circuit is 7 decibels, and without any stabilization it would have been at least 20 decibels. In connection with the application of the 2-band system to land cables as well as sea cables, perhaps the author will indicate the effect of impedance irregularities. Any serious change of impedance will make a 2-wire circuit unworkable, but one of the advantages of the 4-wire circuit is that even if one or two loading coils break down, thereby completely upsetting the impedance, the circuit can still go on working. One would imagine that as regards sensitivity to this kind of trouble the 2-band system would be intermediate between the 2-wire and the 4-wire systems.

Dr. A. Rosen: There are three classes of submarine cables in use for telephony at present—the non-loaded, the continuously-loaded, and the coil-loaded types—and these are characterized by the width of the frequency band that they transmit. Of the cables which have already been laid, those which transmit the widest frequency band are found in the non-loaded class, whereas the narrowest frequency band is transmitted by the coil-loaded cables: continuously-loaded cables occupy an intermediate position in this respect. During 1931 a fourth type of cable was developed which combines the desirable characteristics of the other three types. This is an intermittently-loaded cable consisting of alternate sections of continuously-loaded and non-loaded conductors. The sections are comparatively short, so that reflection effects are avoided, and the cable is made up so as to have a uniform diameter along its length. This facilitates handling and laying operations. A cable of this description (see Fig. A) now being made to the order of the British Post Office contains 30 quads and is shortly to be laid between England and

Belgium. In this case the alternate sections of the loaded and plain conductor are ⅛ nautical mile in length, and the cut-off frequency of the cable is in the neighbourhood of 30 000 cycles per sec. Over the working range it behaves as a continuously-loaded cable, but it has a flatter attenuation/frequency curve and a greater useful band width than the usual cables of that type (see Fig. B). For example, the overall attenuation at 2 400 cycles per sec. is about 3·3 népers (29 decibels), and the attenuation at 8 500 cycles per sec. is about 6 népers (52 decibels). Taking 6 népers as the practical limit for submarine cables, the band width of this cable is 8 500 cycles per sec., which makes it very suitable for a 2-band or similar carrier channel. The transmission time for this cable is approximately the same for all frequencies; for the 50-mile length it is of the order of 2 milliseconds. Comparing these figures with those given in Fig. 11, it will be seen that for a 1 000-km

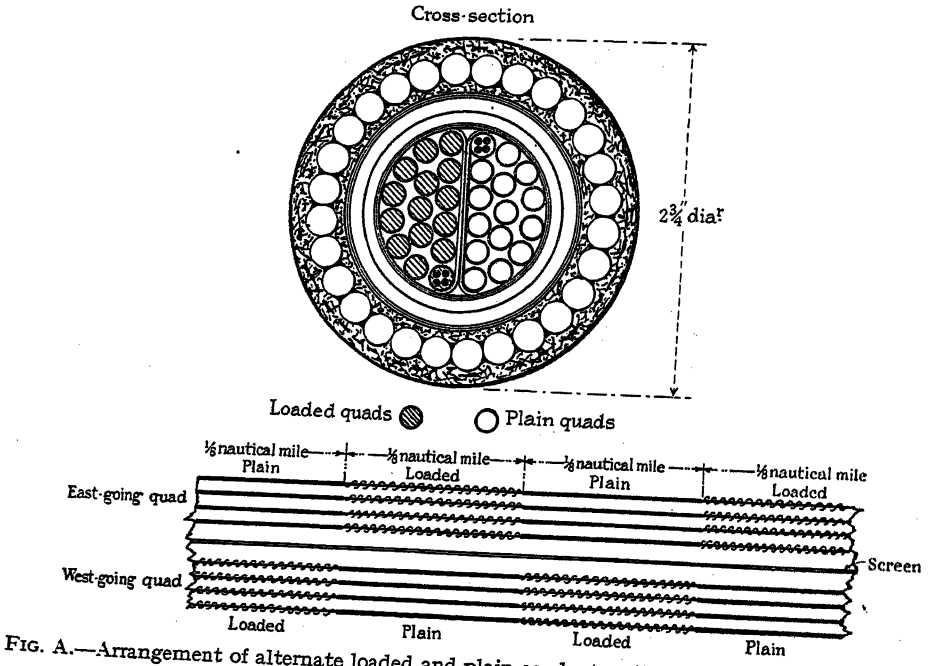


FIG. A.—Arrangement of alternate loaded and plain conductors in Anglo-Belgian (1932) telephone cable. (Intermittent loading.)

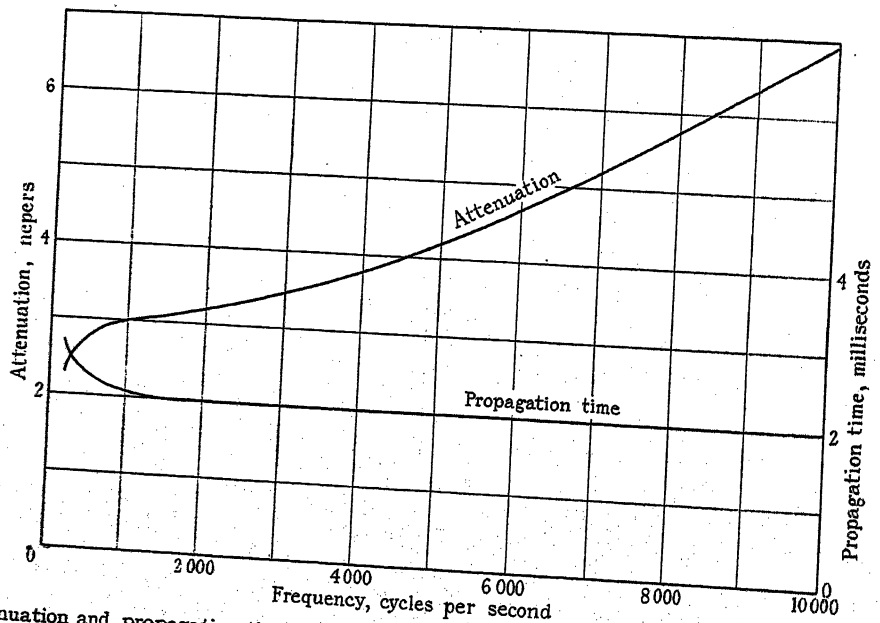


FIG. B.—Attenuation and propagation time of Anglo-Belgian (1932) cable. Length, 50 nautical miles (approx.).

length of this type of cable the transmission time will be only 20 milliseconds, and will be substantially the same for all frequencies within the working range. Figs. 22 and 23 demonstrate the economy of the 2-band as compared with the 4-wire system, and are presumably based on coil-loaded cables. Calculations of the relative costs of the intermittently-loaded and coil-loaded types show an advantage in favour of the former when maintenance is included; this advantage becomes marked when a wide frequency range is required, e.g. for carrier working. Curves corresponding to Figs. 22 and 23, based on the intermittent type of loading, would show off the 2-band system to even better advantage.

(*Communicated*): Two important factors in the design of submarine telephone cables for tidal waters are ease of repair and effect of repairs on performance. Repairs are more difficult when the number of conductors is large; hence it is advantageous to use a cable with a wide frequency band which will permit a carrier system of the 2-band type to be employed. The number of conductors would then be halved as compared with the 4-wire type, and, furthermore, the conductors would be of stouter gauge. During repairs, extra lengths of cable are unavoidably inserted, and these disturb the uniformity of spacing in coil-loaded cables. This factor introduces irregularities into the impedance/frequency characteristics and lowers the cut-off frequency. For this reason a coil-loaded cable designed for 2-band working should have a cut-off frequency of about 7 000 cycles per sec. initially, so as to allow a factor of safety in case of repairs. On the other hand, the intermittently-loaded cable with an initial cut-off frequency of 30 000 cycles per sec. has a wide safety margin. A test in which one of the loaded sections was entirely omitted at a point 4 miles from the measuring end, showed the resultant impedance irregularity to be only 6 per cent, whilst when the omitted section was 24 miles distant the effect was found to be negligible. It should be added that precautions have been taken in the design to prevent the omission of a whole section during repair.

Col. A. S. Angwin: The author stresses the economic side of multiplex radio telegraphy and telephony, and I am not sure that this can be regarded so much in the light of a by-product as it at first appears. It is indisputable that when a number of channels are used on the multiplex system, the power available per channel varies inversely as the square of the number of channels. Taking the example illustrated in the paper of a 20-kW transmitter with 70 per cent modulation on the telephone side and 15 per cent for the telegraph channels, the power available for each telegraphy channel is only $\frac{1}{22}$ of the power of the telephone channel, equivalent to that which would be given by a separate 1-kW telegraph transmitter. The possibility of direct interference tones is avoided by limiting the upper frequency of the telephone channel to the very low value of 2 400 cycles per sec., but a large number of modulation products on a wide range of other frequencies can be produced. While the system of multiplex described in the paper has many interesting features, I suggest that the two factors of limitation of available power and liability to intermodulation effects are economically adverse to the application of multiplex to radio telegraphy.

Mr. R. A. Mack (*communicated*): In the second part of the paper the author refers to new developments in the field of the multiple utilization of lines, and as the great technical interest which these new systems excite may detract from a proper appreciation of the merits of the older systems, particularly as to the possibility of obtaining telegraph facilities superposed on telephone circuits, I should like to make some reference to these. The pole route of 20 pairs of wires mentioned on page 782 doubtless includes a d.c. telegraph circuit of the "composite" type between each wire and earth. Using similar principles, modern telephone-cable circuits can yield one d.c. telegraph circuit for each metallic pair in the cable, without interference between the various telegraph circuits or between these and the telephone circuits (the so-called "metallic composite system"). Such additional telegraph facilities are obtained on the shorter-range circuits at a comparatively trifling cost. When the telephone line has repeaters, these have to be equipped with by-passing circuits, so that costs increase as the line becomes longer and the number of repeaters increases. With the voice-frequency carrier telegraph systems the equipment is wholly at the terminals, and thus, the costs being independent of the circuit length, the voice-frequency carrier telegraph system can be economically justified on both longer medium-range and long-range circuits, whereas the economic field of metallic composite circuits extends only to circuits of medium range. An alternative means of securing additional telegraph facilities at low cost, particularly where paired or star-quad cables are favoured, is by simple telegraph phantom circuits, or alternatively by superposing telegraph super-phantom circuits on telephone phantom circuits, but the number of circuits obtainable by such means is considerably less on a given cable than are provided by the use of the metallic composite system. This system (metallic composite) has hitherto been almost entirely neglected by European administrations, although in other countries it has been widely applied with striking success and economy. There can be little doubt that the growing application of teleprinters to the telegraph service will cause considerable expansion in the use of both the metallic composite and the super-phantom systems. There are at present in Europe thousands of miles of telephone pairs upon which these potential facilities are lying idle.

Mr. E. S. Ritter (*communicated*): I should like to draw attention to certain features of telegraphy which may be misunderstood by telephone engineers. Telegraphy may be defined as the setting of a piece of metal (the armature of a relay situated at the receiving terminal) in one of two, or possibly three, positions during predetermined time-intervals or portions thereof. The interval is known as a "baud," and the telegraph speed in bauds is the number of these intervals in a second of time. In most of the systems in use there are two positions for the receiving relay, but in cable morse there are three. The different telegraph systems require a varying number of signal elements to represent the letters of the alphabet (e.g. the Wheatstone morse system), or a constant number per letter (e.g. the Baudot or other 5-unit codes), or a single timed unit sent at irregular multiples of the unit interval (e.g. the Hughes

system). The signal elements may be sent out continuously and at a constant speed (e.g. the Baudot and certain other multiplex systems), or at a variable speed (e.g. the Wheatstone and Siemens high-speed systems), or intermittently at a constant speed (e.g. start-stop or teletype systems). All the above systems will tolerate a certain amount of distortion in the signals; speaking generally, if the receiving element is in the correct position during the middle 60 per cent of the signal the apparatus will translate the signal correctly. Telegraphy differs from telephony in that it is possible to interpolate repeaters, one type of which will send out new signals of correct amplitude but distorted in regard to the time at which they entered the repeater, and a second type—known as regenerative repeaters—which will send out the signals correct in time and amplitude provided the speed of transmission and the system of working is predetermined. In comparing systems the author uses the letter of the alphabet as the measure of intelligibility. While it is doubtful whether this is a correct method, no better one appears to be available at present. In telephony, personality is transmitted in that the listener is frequently enabled to recognize the speaker's voice; a picture system enables one to identify handwriting; and in telegraphy the intelligence-carrying capacity of a letter may be increased several times by the use of a code book. In the first part of the paper the author considers telegraph devices having two positions and operated by change of amplitude, and in the second part he mentions a system operated by change of frequency (in conjunction with change of amplitude). There is a further possible system, depending upon change of phase, which will admit of three position signals being received. In this system a carrier current is sent to a distant point; for signalling it may be suppressed and/or its phase reversed with respect to a local carrier current of exactly the same frequency at the receiving end. A wattmeter-type relay will respond both to a change in phase and to a suppression of the carrier current, thus giving three positions. Does it take twice as long to establish the steady-state condition when reversing the phase as it does to suppress the carrier current in a line with phase and amplitude distortion? It would be interesting to know the frequency of the current and the band width of the filter referred to in Fig. 2. The oscillogram shows that it takes approximately 8 cycles to build up the current. Is the band width one-eighth of the carrier frequency? In Table 2, should the noise voltage not have been expressed as a fraction of the maximum received voltage? Is it to be understood that in start-stop telegraphy it is only necessary to transmit 24 cycles with a time-delay between zero frequency and 24 cycles per sec. of 20 milliseconds, in order to obtain perfect reproduction? If so, how is it that in a system of carrier telegraphy using 120-cycle spacing, signals of about 45 cycles per sec. fail, and that the commercial operating speed is limited to about 33 cycles per sec., or 66 bauds? Table 3 indicates that the value of k for teletype would be 18 instead of 7·0, and that k for quadruple Baudot a.c. would be 10·0 instead of 5·4. My reason for mentioning this is to remove the impression that it is only necessary to allow a band width in cycles equal to the telegraph speed in bauds, whereas in practice a considerably wider band is necessary. On page 779 the maximum speed of a telegraph circuit in bauds is given as the inverse of the building-up time in seconds: is this strictly accurate, having in mind the type of oscillation shown in Fig. 10, and also the fact that most types of telegraph apparatus will take some distortion without detriment? Do these two factors cancel out? In telegraphy the abbreviation "d.c." usually stands for "double-current," whereas in the paper it is presumably intended to mean "direct current."

Dr. L. E. Ryall (*communicated*): The advantage of lightly loaded cables for reducing transmission time, and the consequent echo and phase-distortion troubles, is indicated in the paper. A further advantage is that, owing to the smaller inductance of the loading coils used, the non-linear distortion due to the hysteresis of the coils is considerably reduced. The use of inductance coils in the phase-correcting networks will also give rise to an additional non-linear distortion, although by inserting the networks at points where the transmission level is low, the effect can probably be kept very small. The principle of obtaining telegraph signals free from atmospheric interference shown in Fig. 25 was applied by the British Post Office a few years ago to a voice-frequency system for signalling over trunk circuits, and was found to be quite immune from false operation by speech signals. Alternate signal pulses of 450 and 550 cycles per sec. were transmitted, causing a relay armature to vibrate at the receiving end of the circuit. These vibrations were used to control the operation of an auxiliary relay. The method was later abandoned as being unnecessarily complicated for the purpose in view. It is interesting to note that in Table 3 the constant k for telephone speech is 160 times the lower limit of k. I think the reason for this, apart from the fact that words are not the most efficient means for conveying ideas, is that telephone speech conveys naturalness, tone, and other characteristics of the speaker's voice besides word intelligibility. Theoretically, at any rate, I believe it should be possible to reduce the frequency band width of speech, thereby sacrificing some of the individual characteristics associated with different speakers, without sacrificing intelligibility. Thus the statement on page 776 that "the endeavours of numerous inventors to obtain a more efficient transmission system . . . will always remain unfruitful," does not appear to be borne out by the information given later in the paper.

[The author's reply to this discussion will be found on page 795.]

North-Western Centre, at Manchester, 5th April, 1932.

Mr. T. E. Herbert: The standard arrangement of open wires on a pole line which is shown in Fig. 19 actually gives 54 telephone and 80 telegraph circuits, not 70 telephone and 80 telegraph circuits as stated by

the author. The latter number of circuits is given by the later arrangement, where phantoms are not employed and a slightly different spacing between the insulators is used. I do not think that carrier circuits on aerial lines are likely to be of any particular value in Great Britain, except in case of emergency. The Post Office Research Department has designed a single-channel carrier system, operated from a.c. supply mains, which is capable of establishing a zero circuit for any aerial line whose attenuation is less than 30 decibels at 9 kilocycles per sec. The system employs a common carrier frequency for the two directions of transmission, and transmits the upper side-band in one direction and the lower side-band in the other. The apparatus required is quite simple, small, and compact. It can be fitted on a rack or alternatively it can be made up in box form. Sub-audio telegraphy has also been used in some cases, particularly on the Channel Islands cable. I should like to ask the author what is the allocation of costs in the case where a pair of wires is used for several purposes. For example, if a pair of wires provides a telephone speech channel and a telegraph channel, how are the costs allocated between the two services? Is half the cost charged to each service, or is the cost allocated in the proportion of the band frequency which each service uses? When an alternating current is applied via a filter, what is the difference between the effect of applying the voltage at the zero point of the cycle and at some other point? A great many years ago a telegraph known as a "sychronograph" was devised in which an alternating current was employed and signalling was carried out by cutting off the top or the bottom half-waves. The speed of transmission obtainable by that system was three times that of the Wheatstone method. Hence I should be glad to know whether an improvement in building-up times could be achieved by some form of apparatus where the contact is made to the filter at the moment when the wave is passing through zero. There seems to be a big future for the thermionic-valve form of relay which has recently been devised by Mr. G. T. Evans, of the Post Office Engineering Department. In many cases trouble is caused in telegraph signalling as a result of the defects of the ordinary mechanical relay. Finally, I should like to refer to the difficulty of solving communication problems by considering transient conditions. For example, the problem of the loading necessary on a double-phantom telegraph circuit is intractable when attacked by the method of transients, but when it is tackled by classical alternating-current theory a solution is arrived at which can be proved to be correct by practical tests.

Mr. T. B. Terroni: Fig. 3 is interesting in that it shows that the breaking of a 125-cycle pulse dies away in oscillations of 43 cycles per sec., which is the lower border frequency for this circuit. It would be interesting to have some simple physical interpretation of the die-away frequency, as it appears that the energy stored in the circuit is constrained to dissipate itself at that frequency in the pass range of the circuit which offers the least impedance. Many experiments have been carried out with a view to determining the effect of noise in long telephone circuits, on the articulation of the telephone circuit: have any similar experiments been performed to determine the effects of different delay/frequency characteristics upon the articulation of the circuit? These effects would appear to determine the necessity for phase compensation in marginal cases.

Mr. W. Jackson: I should like to make an addition to the first portion of the paper by introducing two terms which are employed to express the complete distortion experienced by a signal following its sudden application to a communication circuit, namely the "transient distortion" and the "frequency distortion." The use of two different names to express the same change in wave-form of the signal arises from the existence of two different mathematical methods of treating the problem—the transient method and the steady-state method. When it is possible to obtain a solution which takes into account all the circuit characteristics, the transient method provides at once a complete statement of the building-up process of current under suddenly-applied driving e.m.f.'s, and therefore a complete statement of the signal distortion. When derived in this manner the distortion is referred to as the transient distortion. It is difficult to take exact account of the variable characteristics of practical line circuits by this method, and in fact to deal with other than ideal cases, but the transient solution of such cases is invaluable in providing a basis for practical deduction. The solution of the transient problem of an ideal loaded submarine telegraph cable, for example, is of great value in giving a physical picture of how inductive loading aids the high-speed transmission of signals. Steady-state analysis, on the other hand, deals with continuing conditions, and regards suddenly-applied signals as an infinite succession of sustained sinusoidal components. These can be considered individually by well-known methods, given a knowledge of the admittance/frequency characteristics of the transmission system over the entire frequency spectrum, and, in the complete analysis, they give the same statement of the signal distortion as that provided by the transient method, subject to the same conditions of analysis. This statement is frequently referred to as the frequency distortion, and is given in component parts as the amplitude or attenuation distortion and the phase or delay distortion. If this method is adopted no difficulty arises in taking account of the variable loss/frequency characteristics of practical circuits in the transmission band, or of non-linear distortions. Which of the two methods is adopted depends on the object to be secured. The former, when it can be applied, gives much more readily and concisely a complete statement of the distortion and leads to results which fit in better with the method of measuring information developed by Hartley.* On the grounds of simplicity, however, the latter possesses undoubted advantages from the point of view of the practical communication engineer. If the attenuation and delay of a system are equalized over the entire frequency spectrum, the building-up time of a suddenly-applied signal must be zero and no transient distortion can arise. In practice, however, this does not occur, and in fact for many applications the transmission is purposely limited to a finite band of frequencies. If, for example, a band filter is introduced into an otherwise

* *Bell System Technical Journal*, 1928, vol. 7, p. 535.

distortionless system, the modified forms of the attenuation/frequency and phase (or delay)/frequency characteristics of the entire system must show themselves as a transient distortion on the sudden application of a signal. I mention this because consideration of the oscillogram of Fig. 2 seems liable to give the impression that the transient distortion of which the oscillogram is a record is due entirely to amplitude distortion, whereas variations of the delay characteristic over the transmission band, and particularly in the region of the cut-offs, also play an important part. In fact, the elongation effect which would have been evident had the end of the signal also been shown is due primarily to delay distortion. This elongation effect is well brought out in Fig. 12. In connection with these oscillograms, it should have been mentioned that the greater distortion with the 2 000-cycle wave is probably due to the fact that the delay characteristic is changing more rapidly in this region than in the region of 1 000 cycles per sec. In connection with the simple law stated on page 777 to the effect that the building-up or transient time is equal to the inverse of the band width, it should be appreciated that this is only approximate, since the instant at which the building-up process ends and the current reaches its steady value does not admit of precise definition. The appearance in current literature of two forms $(\alpha + j\beta)$ and $(\beta + j\alpha)$ for the propagation constant is liable to be somewhat misleading to students of electrical communications, and it would be of advantage if an official ruling by the C.C.I. or other authoritative body could be given in favour of one of these forms.

Mr. J. M. Jackson: With regard to distortionless transmission (page 777), if the attenuation α is consistently reduced will the actual speech received be distortionless? Turning to the subject of carrier-current telephony (page 782), it was decided that in this country it was only economical to apply this system to long lines, and it has therefore not been generally adopted over here. I believe, however, that it has found some favour in Australia. I should like to congratulate the author on the way in which he has brought to our knowledge the effect of phase distortion and echoes by means of gramophone records.

Mr. W. K. Dunn: I shall refer first to the statement on page 776: "A proper choice of the velocity permits of enlarging or narrowing the frequency band to any desired amount, but the time required for the transmission of a given quantity of information increases or decreases in the same ratio." It is believed that, since the frequency of the sound emitted by the rotating disc increases in direct proportion to the velocity of rotation, and the time required to emit a given number of undulations grows less as the velocity increases, the transmission time varies inversely as the velocity. I should be glad of the author's observations on this view. His use of gramophone records to illustrate certain points suggests that picture transmission might be almost equally valuable for this purpose. The faults common to this type of transmission fall into the three natural groups of photographic, mechanical, and electrical. Mechanical defects, such as gear lash, dirt, and asynchronism, are common to many types of apparatus. The results, and even their remedies, are obvious in most instances. Photographic faults are also of a common type, and they are readily discernible in the finished product. When the faulty pictures have been segregated from the remainder, a wide range of the electrical defects in a transmission system can be recorded and investigated. In picture telegraphy by a unidirectional transmission, one does not encounter the important difficulty of the transmission time which is met with in telephony. The building-up time of the carrier is of importance, however, and it should not exceed 1·2 milliseconds without the introduction of phase compensation. It is approximately equal to the difference between the transmission times of the lower cut-off frequency and the carrier frequency, and between London and Berlin this amounts to about 1·4 milliseconds. The value of echo suppressors was clearly illustrated in a picture sent over a London–Leeds loop using a 4-wire circuit without suppressors. On the received picture the image was repeated until it gradually died away, as in the acoustic case. A peculiar plastic effect was also produced by incorrect compensation on the photo-electric cell, which gave the impression that the "sent" picture was a negative print of a bas-relief. Differences in line level are well illustrated in this system, and the value of the change may generally be inferred from inspection.

Mr. S. Jackson: I should like to ask whether, by more accurately matching the impedances at repeater stations and the use of suitable phase equalizers, possibly at each repeater station and at the terminations, it would be possible to do without echo suppressors on 4-wire circuits. Our chief practical trouble is distortion, and it is thought that by eliminating the cause of the echo and consequent distortion in its early stages, i.e. at the points of reflection at each repeater, the quality of speech between terminal stations could be improved and possibly the use of echo suppressors would not then be necessary. I should be glad if the author would give his opinion in this connection.

Mr. A. H. C. Knox: The problem of getting circuits across the very narrow strip of the English Channel from Kent to the Continent must present considerable difficulty, and the development of modern communications along the lines of multi-channel systems should go a long way towards helping us to solve this problem. As far as the inland system is concerned, the scope for multi-channel systems would seem to be limited. Main aerial lines are disappearing rapidly, and the principal application of the system would appear to be the running of two channels on a pair of wires so that they can be changed over in case of a break in the physical circuit. This should be cheaper than running new wires, especially if the rebuilding of a route is involved. In some tests of carrier-system channels in Australia, 38 channels between Perth and Sydney were linked together to form a telegraph circuit of 36 440 miles. The average time-delay was found to be 0·71 sec., this being the time taken for the signal to traverse the whole 36 000 miles. With regard to interference, multi-channel systems with carrier frequencies have an advantage over audio-frequency systems in that the harmonics of a low-frequency power supply will be well clear of the carrier frequency. On the British "grid," however, the considerable lengths of underground cable which have been

introduced into main overhead lines will produce very serious reflection losses unless some special steps are taken to overcome this difficulty. Tests at frequencies of from 20 to 100 kilocycles per sec. have been made at the Post Office Research Station on a 100-yard length of special cable manufactured by Messrs. Siemens Bros. At 70 kilocycles per sec. the characteristic impedance was $574 \cdot 9, \angle 3° 15'$, the attenuation constant 1·194 népers per mile and the phase-constant 14·41 radians per mile. If we can get short cables to transmit frequencies up to 70 kilocycles per sec., the reflection difficulty will probably be considerably reduced. In the earlier days of manually-operated telegraphic systems phase distortion was perhaps not so important as it is under modern high-speed conditions. With the advance of machine printing systems requiring a synchronous relationship and in which the essential point is that the signal impulse must be applied in correct phase, phase distortion enters considerably into the problem. The author's practical demonstrations of distortion have shown how important this question is.

Mr. R. H. Hunt: It would appear that the development of carrier telephony and telegraphy has gone on rather more rapidly in Germany and the U.S.A. than in this country. So far as Germany is concerned I believe this is due to the fact that her cable system was rapidly reconstructed about 14 years ago, when it was clear that considerable time would be saved by applying carrier working rather than superposed circuits. In the U.S.A., owing to the length of the lines over which messages are transmitted, and also because of the private-wire telegraphs which are very widely rented, the carrier system proved very successful. In this country, on the other hand, we had a fairly extensive and efficient underground telegraph system working chiefly on the Baudot multiplex plan, and the need for a carrier system was not quite so urgent about the time of its inception in Germany and the U.S.A. Now that the demand for private-wire telegraphs is arising in this country, there is likely to be a great extension of the carrier system on the telegraphs carried in local-line cables. That part of the paper which deals with American overhead practice is especially interesting. I understand that the Americans use the transposition method of avoiding interference between pairs and open lines, whereas in this country many circuits are run on the symmetrical-twist system, which is likely to cause a considerable amount of cross-talk between pairs or sets of wires carrying the same frequency. Presumably, allowing for the carrying of as many as 80 telegraph and 70 telephone circuits, there would be some circuits which would work on the same frequency, although they might be rather far apart on the arms of the group. Even when the lines are transposed at comparatively long intervals cross-talk still occurs, and at certain frequencies it may be sufficiently severe to cause appreciable absorption of energy. The cure, of course, is more frequent and accurate transposition, but the limit to this is set by the length of individual spans. It would not pay to shorten the length of the span for the sake of reducing cross-talk. High-frequency disturbance from radio stations may perhaps cause trouble, but I understand that low-frequency harmonics from power wires do not affect the carrier circuits. As regards cable construction, the high-resistance "skin" effect of high-frequency currents will probably lead to the use of stranded conductors in telephone cables, which would require a considerable alteration in jointing technique and in the manufacture of the cables. It is rather significant that Graham Bell discovered the telephone when he was working on a system of harmonic telegraphs which, I believe, was inaugurated by Mercadier. It is appropriate that the work of the two men should be associated with such success by the author and his colleagues.

Mr. W. Stretch: With regard to the instantaneous change shown in Fig. 8, I do not follow the author when he says that the amplitude spectrum has become a continuous spectrum. Consider the square-topped wave; however long the period is made, the curve can still be represented by a series of sine or cosine terms, the frequencies of the components all being integral multiples of the fundamental frequency. While it is true that as the period is made longer the frequencies shown in Fig. 6 lie closer together, even for the longest periods one would still expect to have only the odd integral terms of the series. Fourier develops the series for the instantaneous change by considering a finite period of time which includes the moment of the change. He states that to consider a period equal to infinity leads to an incorrect result. The transient curve shown in Fig. 10 could, in fact, have been obtained by taking the first three terms of the series. I should be glad if the author would clear up this point in his reply. In connection with Fig. 24, I notice that—assuming the suppression of one side-band—a radio-frequency channel of 5 650 cycles per sec. is occupied in the simultaneous transmission of speech and telegraph signals. The frequency bands actually utilized, however, only amount to some 2 200 cycles per sec.; i.e. less than half the channel. The reason given is that by this means the speech channel is kept clear of interference caused by the telegraph frequencies. I take it that such interference would be caused by non-linear distortion arising in the apparatus. If so, would it not be desirable to avoid non-linear distortion in the apparatus and thereby to conserve the available wavelengths? It is interesting to note that the system described uses two methods of modulation, namely amplitude modulation for speech, and frequency modulation for telegraph signals. The author makes no mention of frequency modulation for the transmission of speech: I understand that the frequency-modulation method requires a much narrower wavelength band than the amplitude-modulation method. Has he any information as to recent progress in the frequency-modulation method for the transmission of speech by radio?

The Author's Reply to the London and Manchester Discussions.

Dr. F. Lüschen (*in reply*): In dealing with the numerous points raised in the discussions it seems to me to be advisable to make use of a classification similar to that adopted in the paper. My replies to the questions raised by various speakers will therefore be grouped under three main headings.

(1) *Two-Band Systems.*

The 2-band system has everywhere aroused great interest, and for British communication engineers its chief attraction naturally centres round the question whether the system would be of advantage for the submarine cables terminating in their own country. Generally speaking, normal 2-wire submarine cables differ fundamentally from 4-wire and 2-band submarine cables as regards permissible maximum attenuation; in cables containing several speaking circuits this quantity is about 15 to 25 decibels for 2-wire, and about 80 decibels for 4-wire and 2-band systems. A high attenuation means a saving in copper; on the other hand, for mechanical reasons the conductor gauge should not be made less than 1 mm. The permissible attenuation of 80 decibels for 4-wire and 2-band systems therefore renders such systems economically advantageous only for cables exceeding a certain length. This is shown in Fig. C, where the relative costs of some types of submarine cables are plotted against the cable length. The 2-band system clearly offers economic advantages for lengths from 80 to 480 km, as compared with the other systems.

The method referred to by Sir Thomas Purves, and used by the British Post Office, of employing 2-wire cables for shorter submarine routes and obtaining stability on the connected 4-wire circuits with the aid of automatic stabilizers, is very remarkable. It should be remembered, however, that owing to its sensitivity to line interference and the consequent loss in operating time, the stabilizer is not yet an ideal piece of apparatus. Its defects are particularly noticeable if several stabilized circuits are connected in series, as appreciable disturbances may then be set up.

Captain Timmis raises the question of the stability and sensitivity of 2-band cables with respect to impedance variations. In regard to instability and insensitiveness due to variations in the cable impedance produced by repair work and the like, a 2-band system is absolutely equivalent to a 4-wire circuit, and even impedance variations of considerable magnitude do not prejudice stability and operation. A 2-band cable therefore differs essentially from a 2-wire cable, where each serious variation of impedance may put the line out of service.

Captain Hines and Captain Timmis mention, in addition, the multiple utilization of a continuously-loaded cable between England and Holland. The method of obtaining 16 2-wire circuits by means of 4 continuously-loaded quads, repeatedly phantomized, and finally superimposing a carrier telephone circuit on each of the 4 quads, is very interesting. Where 2-wire circuits are permissible and repeated phantomizing can be adopted without giving rise to cross-talk, such a system doubtless offers economic advantages—even for greater cable lengths—as compared with other systems. A rough survey is given by Fig. D, where the costs of a continuously-loaded cable having 4 quads and an attenuation of 20 decibels are compared with those of a continuously-loaded cable having an attenuation of 80 decibels and including 6 quads. In the first case (4 quads), 14 2-wire circuits and 4 carrier circuits (18 circuits in all) have been assumed. The 6 quads result in 12 2-band and 6 carrier circuits, i.e. also in 18 circuits. For lengths exceeding 200 km, the 2-band cable is cheaper than the 2-wire cable, but for lengths of less than 200 km the use of repeatedly-phantomized 2-wire cables is doubtless a very economical solution.

As to the question raised by Mr. Werren regarding the comparison of the costs of 2-band and 4-wire systems given in Figs 22 and 23, I would refer him to the original paper by H. F. Mayer and G. Mücke.*

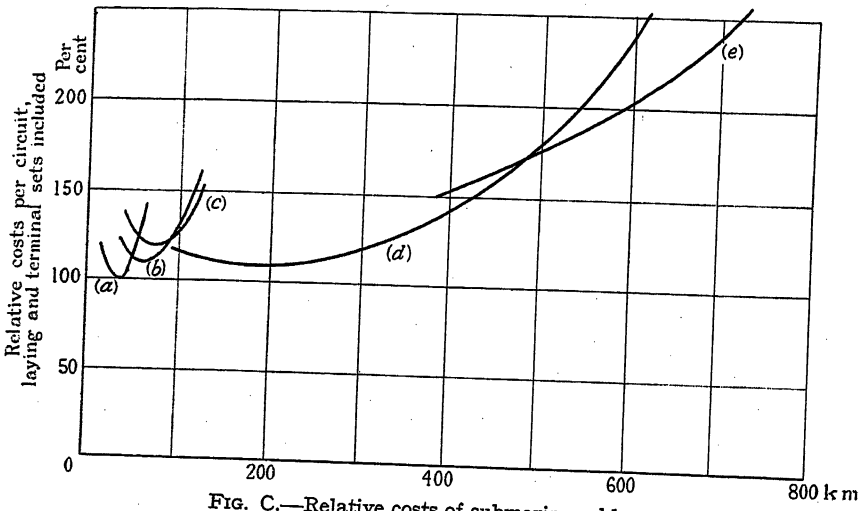


FIG. C.—Relative costs of submarine cables.
(a) Two-wire non-loaded, 25 decibels at 2 400 cycles per sec.
(b) Two-wire coil-loaded, 15 decibels at 2 400 cycles per sec.
(c) Four-wire non-loaded, 80 decibels at 2 400 cycles per sec.
(d) Two-band coil-loaded, 80 decibels at 5 500 cycles per sec.
(e) Four-wire coil-loaded, 80 decibels at 2 400 cycles per sec.

(2) *Multiple Utilization of Short-Wave Links.*

Col. Angwin points out that in the multiplex utilization of wireless transmitters the energy available per

* "The Economical Use of Two-Band Telephony on Coil-Loaded Submarine Cables," *Europäischer Fernsprechdienst*, 1930, no. 20, p. 370.

channel decreases as the square of the number of channels, and that considerable coupling is likely to occur in the transmitters owing to inter-channel interference. These circumstances greatly limit the possibility of multiplexing transmitters. In the case under consideration (Berlin–Buenos Aires), however, only one transmitter was available which handled the entire telegraph service, and, at certain hours, the telephone service also; hence interruption of the transmission of telegraphic messages was not permissible. In this case the multiplex system has proved very successful. It was first intended to provide for two independent telegraph channels (2 700 to 2 800 and 5 550 to 5 650 cycles per sec.) in addition to the speech band: but in the course of the tests it was found to be better to operate the second channel at 5 400 to 5 600 cycles per sec., i.e. harmonically with respect to the first, and to combine the two to form only one telegraph channel. This frequency allocation proved extremely insensitive to the fading of the carrier wave. The fact that this multiplex channel with an output of 80 watts per channel yielded better

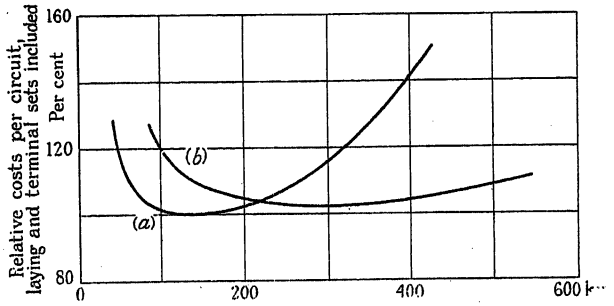


FIG. D.—Relative costs of continuously-loaded submarine cables.

(*a*) 4 quads, repeatedly-phantomized; 14 2-wire and 4 carrier circuits, 20 decibels.
(*b*) 6 quads, non-phantomized; 12 2-band and 6 carrier circuits, 80 decibels.

results than did an ordinary 20-kW telegraph transmitter, means that the usual telegraphic methods might still be improved. The technical superiority of the multiplex telegraph channel can be ascribed to the following features:—

(*a*) Voice-frequency modulation permits of using, at the receiving end, selective low-pass filters, by means of which the signal/noise ratio can be given a favourable value.

(*b*) The use of two closely adjacent frequencies for marks and spaces has the advantage that disturbances affecting both frequencies neutralize one another, owing to the differential action of the receiving relay.

(*c*) A low-frequency receiving current which emanates either from the mark or from the space is permanently present at the receiver, and this can be used as a very rapid automatic fading control, principally for dealing with selective fading.

(*d*) The combination of such a double-current channel with another harmonic double-current channel practically eliminates the effect of carrier-wave fading.

The application of these principles to the transmission of one telegraphic message from a telegraph transmitter will considerably increase the reliability of communication. The results of experiments in this direction justify the assumption that these principles will enable printing telegraph apparatus to be introduced into wireless telegraphy.

(3) *Fundamental Transmission Problems.*

The "steady-state" method is used in the paper for dealing with transient phenomena in transmission systems, and it is therefore interesting to have Mr. W. Jackson's assurance that these problems can also be solved by the "transient" method. Both methods lead, of course, to the same result, and the choice of one or other depends only upon their relative suitability in the particular case under consideration. In simple cases, as, for instance, the charging of a condenser through a resistance, the transient method is the more efficient. In problems dealing with the transmission of a.c. signals over complicated systems, such as long trunk cable circuits, the steady-state method is preferable. The advantage of this method is that it does not demand a knowledge of the details of the system. It is only necessary to know the attenuation/frequency and phase/frequency characteristics for given terminal conditions, and these can be obtained either by calculation or by means of a.c. measurements. The steady-state method has the advantage that it enables one to establish the condition of distortionless transmission

$$\alpha = \alpha_1 \qquad \beta = \omega t_0$$

for any given system. The fundamental criterion for the design of electrical transmission systems, i.e. that they should transmit all frequencies equally well and should enable the phase to increase in a linear way with frequency, is a deduction from this condition. In addition, two simple rules may be arrived at for the cases where:—

(*a*) The frequency band is restricted to a definite range (without appreciable phase distortion).

(*b*) The phase does not vary in a linear way with frequency (without appreciable amplitude distortion).

The rule for case (*a*), which chiefly refers to the transient phenomenon of an a.c. signal within a narrow band-pass filter, is

$$(\text{Band width}) \times (\text{Building-up period}) = 1$$

For case (*b*), which chiefly refers to the transient phenomenon of an a.c. signal due to phase distortion in long telephone cable circuits, the rule is

$$\text{Building-up period} = (\text{Signal-frequency delay}) \sim (\text{Minimum delay})$$

Mr. W. Jackson is of the opinion that the characteristic of the dying-out phenomenon shown in Fig. 2 differs from that of the building-up phenomenon, and that phase distortion plays an important part in this connection. This is not the case, for the dying-out phenomenon may be regarded as the building-up phenomenon of another signal of the same amplitude and frequency which is added to the first signal with reversed phase. To obtain the dying-out phenomenon, it is therefore only necessary to subtract the building-up value from the steady-state value. With narrow band-

filters such as are used in a.c. telegraphy the building-up and dying-out phenomena are, in fact, almost invariably determined only by the width of the pass band, although it is conceivable that in some cases phase distortion plays an important part within the pass band.

This is also a reply to the question raised by Mr. Ritter as to what building-up phenomena are to be expected in a telegraphic method involving phase reversal of the transmitted signal and compensation of one phase by a local generator at the receiving end. In this telegraphic method we have exactly the same building-up periods as are obtained when the input voltage is cut in and out. Amplitude modulation and phase modulation are thus entirely equivalent with respect to the required band width and keying speed.

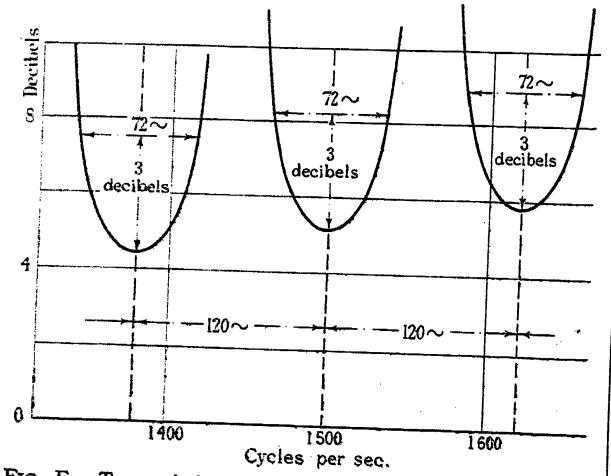


FIG. E.—Transmission ranges of carrier-current telegraphy.

Mr. Ritter's contribution to the discussion includes an interesting interpretation of the formula

$$(\text{Building-up period}) \times (\text{band width}) = 1$$

to the effect that the number of periods involved in the building-up phenomenon is equal to the ratio of signal frequency to band width. For the case portrayed in Fig. 2 the signal frequency was 640, the band width 80 cycles per sec., and the number of periods involved in the building-up period about 8, as may be seen from the oscillogram. Mr. Ritter doubts whether a band filter whose pass band is N cycles per sec. is sufficient to transmit N bauds, and he mentions a voice-frequency telegraph system which, though operated at a spacing of 120 cycles per sec., is only capable of transmitting 66 bauds. Fig. E gives the explanation; the spacing of carrier frequencies is indeed 120 cycles per sec., but the band width of the telegraph channels is only 72 cycles per sec. This value fits in quite well with the obtainable speed of 66 bauds.

With regard to Fig. 12, Mr. W. Jackson is of the opinion that the longer building-up period of the a.c. signal of 2 000 cycles per sec. as compared with the signal of 1 000 cycles per sec., is due to a more rapid variation of the delay characteristic. He evidently has in mind Carson's work* on this subject: when applied to coil-loaded circuits, however, this gives results which are contrary to experience. Both the signals recorded in Fig. 12 begin after 86 milliseconds, i.e. after the minimum delay inherent in the line. The delay for 1 000 cycles per sec. is 90 milliseconds, and for 2 000 cycles per sec. 104 milliseconds; the corresponding building-up periods are 4 and 18 milliseconds respectively.

Turning to Fig. 3, Mr. Terroni asks for an explanation of the fact that the a.c. signal of 125 cycles per sec. dies out in oscillations of 43 cycles per sec. This phenomenon is not due to phase distortion; it may be deduced by the steady-state method from the presence of a lower border frequency of 43 cycles per sec.†

Mr. Stretch doubts whether the voltage step shown in Fig. 8 has a continuous spectrum. As is well known, the voltage step can be represented by

$$\phi(t) = \frac{1}{2} + \frac{1}{\pi}\int_0^\infty \frac{\sin \omega t}{\omega}\, d\omega$$

A feature of this function is that it vanishes for negative values of t, and has the value + 1 for positive values. It is thus the exact mathematical expression for the voltage step. The voltage step accordingly contains a d.c. component ($\frac{1}{2}$) and an infinite number of infinitesimal a.c. amplitudes $[1/(\pi\omega)]d\omega$ of any given frequency ω. Such a spectrum is called a "continuous spectrum."

Mr. Stretch is furthermore of the opinion that frequency modulation requires, in principle, a narrower frequency band than does amplitude modulation. The amplitude modulation of a transmitter by a low-frequency band of definite width produces, in addition to the carrier, two side-bands having the same width as the low-frequency band. For faultless transmission of information it is sufficient to transmit one side-band. The minimum permissible band width in a high-frequency system is therefore equal to the original band width in the low-frequency system. This theorem holds good for frequency modulation, which also produces two side-bands. These, however, are not of the same phase as those produced by amplitude modulation, and for both transmitting and receiving use must therefore only be made of one side-band. The high-frequency transmission range must in such cases at least cover the entire width of one side-band, exactly as in the single side-band method of amplitude modulation.

* J. R. CARSON: "The Building-Up of Sinusoidal Currents in Long Periodically-Loaded Lines," *Bell System Technical Journal*, 1924, vol. 3, p. 558.

† H. F. MAYER: "The Transmission of Broadcast Programmes over Cable Circuits," *Telegraphen-und-Fernsprech-Technik*, 1931, vol. 20, p. 204.

A PRACTICAL INVESTIGATION INTO THE DESIGN OF BRUSHES AND BRUSH HOLDERS.*

By P. HUNTER-BROWN and C. J. HEWS, Associate Members.

(*Paper received* 13*th April*, 1932.)

SUMMARY.

A systematic investigation with the aid of an oscillograph into the behaviour of brushes running on a short-circuited commutator is described. Each brush was divided into two or more parts insulated from each other so that the distribution of current across the face of the brush could be examined. The difficult problem of reversible running received special consideration. The commutator contained a slightly high bar and two flats in order to determine the relative merits of different brush and brush-holder arrangements on an imperfect commutator. A distinction is drawn between the effect of "sudden" irregularities as exhibited by high bars, and of a "gradual" irregularity such as eccentricity of the commutator. The advantages of using a pressure finger of high inertia and the importance of low inertia in the brush itself are demonstrated. Finally, suggestions are made concerning the lines along which further investigation should proceed.

INTRODUCTION.

A good deal has been written from time to time about brush holders from a purely theoretical point of view, usually without taking into account such points as the influence of friction in the holder, inertia of the brush, and the elasticity of the brush and holder. Little, if any, information, the authors believe, has been published concerning the relative merits of different forms of brushes and brush holders as determined by observations under operating conditions. The precise performance is too complicated to permit of accurate prediction by theoretical considerations.

The paucity of information is no doubt responsible to some extent for the diversity of practice with regard to the type of holder employed by machine constructors.

The first part of the investigation described in this paper was directed to examining the contact between brush and commutator and to determining the distribution of current across the face of a brush as influenced by purely mechanical conditions apart from commutation. The method adopted was to divide the brush into two portions circumferentially, insulated from each other and from the brush box but rigidly stuck together to act as a single unit. By means of an oscillograph the current in each half was then determined. At a later stage a brush built up similarly but consisting of four parts was used.

TEST APPARATUS.

The plant consists of a short-circuited commutator built up on a shaft which is run in ball bearings and is driven by a variable-speed motor through a flexible coupling. The rocker has four spindles and is mounted on ball bearings so that the frictional force can be directly measured by a spring balance. Apart from this special feature the plant is devoid of refinements such as could not be expected in ordinary well-built modern commercial plant.

The design details are as follows:—

Commutator diameter:—10 in.
No. of segments:—100.
Pitch of segments:—0·314 in. Mica recessed.
Speed:—1 700/3 700 r.p.m. (= 4 450/9 700 ft. per min.).
Brush holders:—As illustrated in Fig. 1.
Brushes:—As illustrated in Fig. 2. Section throughout 1 in. × $\frac{3}{4}$ in.
Quality of brush:—The grade used throughout was electrographitic such as is usually employed on modern high-speed commutating machines.

In order to imitate conditions that are often met in commercial practice segment No. 1 was raised approximately 0·0005 in. to give a high bar. Nos. 52 and 53 were rubbed down approximately 0·0005 in. to give a flat, and Nos. 72 to 75 were similarly treated.

TEST PROCEDURE.

Test Circuit.—The test brushes were mounted in line circumferentially on one track of the commutator, and the return circuit was made through four highly metallic brushes in parallel, mounted on a different track, one on each spindle. Tests showed that these had a very low and uniform contact resistance, thus exerting a negligible influence on the observations.

The source of supply was limited to three cells of large capacity, so that when voltage tests were made the oscillograph could record the full voltage when the circuit was interrupted. The inductance of the circuit was kept low so as to ensure rapid growth and collapse of the current in the brush as a whole or any part thereof. The diagram of connections is shown in Fig. 3.

Duration of Tests.—These tests were in progress continuously for about nine months. In certain cases the object was to note the immediate effect of a change in conditions. Apart from this, whenever a change was made in the conditions the plant was kept running continuously for several days and no plates were exposed until observation of the oscillograph screen showed that stability had been reached. This was confirmed by the fact that a brush could be removed from its holder, then replaced, and the results repeated.

Method.—The procedure was to run three types of brushes simultaneously during the bedding period and

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

then to disconnect two whilst observations were made on the remaining brush. This ensured that the commutator conditions were identical for all three.

Brush Settings.

The distribution of current in the two halves of each of the three brushes referred to in Table 1, together with

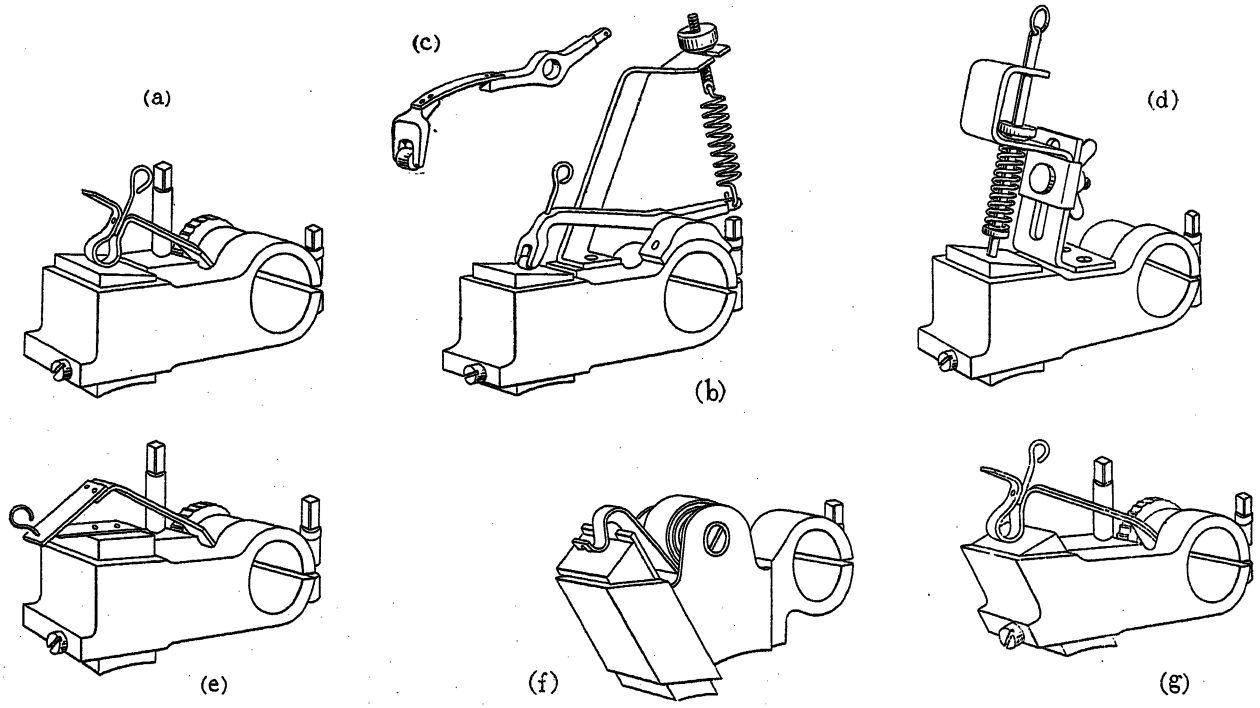


Fig. 1.—Types of brush holders used.

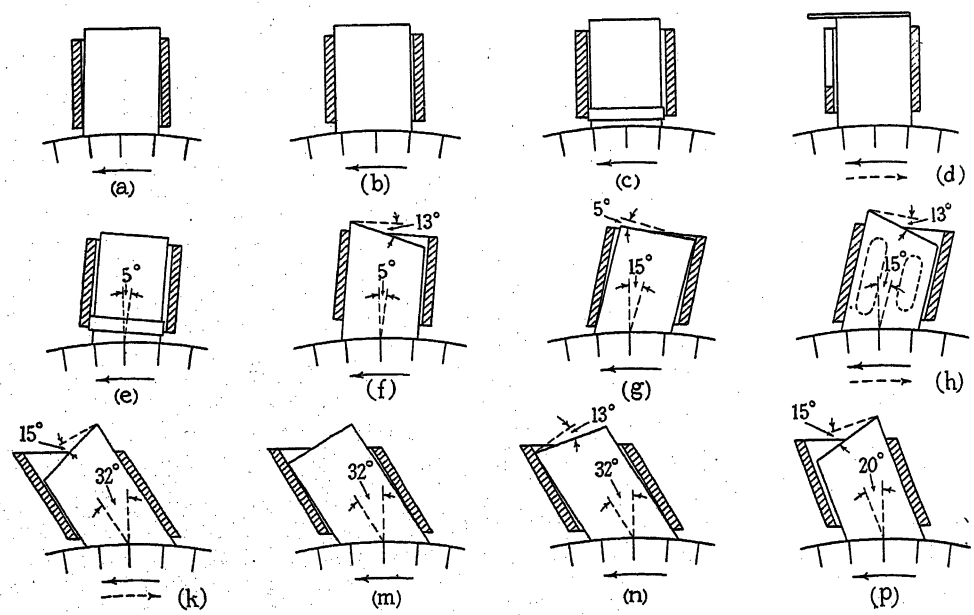


Fig. 2.—Designs of brushes used.

Brush pressure:—2½ lb. per sq. in. of brush cross-section.
Current:—35 amps. (= 47 amps. per sq. in. with one test brush in circuit).
Speed:—2 300 r.p.m. (= 6 020 ft. per min.) except where otherwise stated.

the corresponding contact-drop between brush and commutator, is shown in Figs. 4 to 6.

Referring to the oscillograms it will be noticed how closely the curves shown in Figs. 4 to 6 repeat themselves each revolution, that is to say, the brush movements

synchronize with the rotation of the commutator. Each disturbance can be definitely associated with a particular commutator irregularity. With the exception of the special radial brush (Fig. 2*c*) the natural oscillation period of the brush in its holder plays but a very small part.

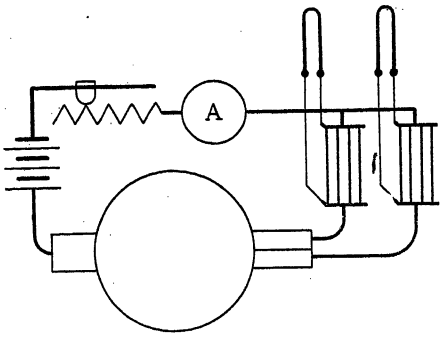


FIG. 3.—Test circuit.

Radial Brush.—Initial tests were made with an ordinary radial brush having a square top in a holder such as Fig. 1(*a*). The brush was first bedded so as to cause it to lie diagonally in the box (Fig. 2*a*) and later wholly against the leaving face of the box (Fig. 2*b*) in an endeavour to obtain stable results which could be repeated at will. Both attempts, however, were wholly unsuccessful and after several weeks of persistent effort were abandoned. A specially shaped radial brush was then prepared which had a rib projecting slightly all round to bear against the bottom edge of the brush box, the object being to ensure that the brush was not constrained by the box near the top but was free to take up its own setting on the commutator. This effected a great improvement and rendered practicable a comparison with the trailing and reaction brushes. It will be

TABLE 1.

Brush		Holder, Fig. No.	Oscillogram, Fig. No.
Description	Fig. No.		
Radial, with square top and projecting rib	2(*c*)	1(*a*)	4
Trailing 15°, 5° top bevel, diagonal in holder	2(*g*)	1(*a*)	5
Reaction 32°, 15° top bevel, brush against entering side of box	2(*k*)	1(*g*)	6

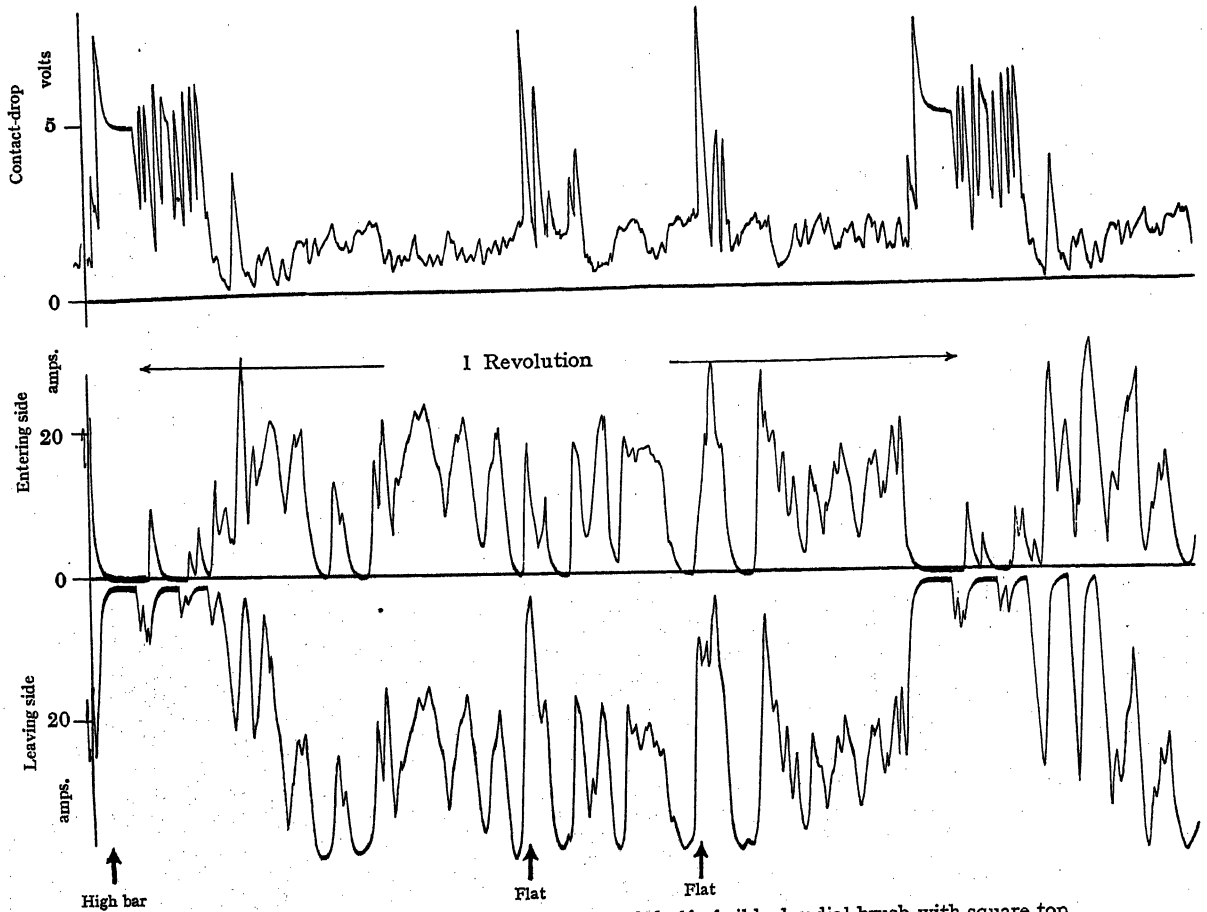


FIG. 4.—Contact-drop and current in each half of ribbed radial brush with square top.

noticed that there is distinct uniformity in the time period of the oscillations (Fig. 4) and that the latter are of considerable amplitude. Their frequency is such that they cannot be associated with any commutator irregularity and must therefore be attributed to the natural frequency of the combined brush and holder. This brush, it will be remembered, is resting against the bottom edge of the box only and is therefore subjected to a minimum amount of damping.

At the high bar the brush leaves the commutator completely for about three segments. The leaving edge then touches the commutator and bounces off, the entering edge touches and bounces off, and the same cycle is repeated for a shorter time. The current oscillates between the two halves of the brush and has not become stable before the flat is reached. Referring to the voltage curve, between segment No. 18 and segment No. 52 at which the first flat begins the voltage is varying, indicating a varying contact resistance, but the current is not actually broken until the flat is reached. The performance can only be described as poor. Moreover, the practical equivalent of the special ribbed brush would be an ordinary plain brush in a very shallow box which is apt to cause trouble due to excessive side wear of the brush.

Trailing Brush.—The trailing brush was running diagonally in its box, touching the latter on the leaving side at the bottom and the entering side at the top. It will be noticed that when the brush passes the high bar the total current is broken for a shorter time than with the radial brush, viz. for about 2 segments. There is no repeat jump, the oscillations are much less violent and are nearly damped out before the flat is reached. The steadier running is reflected in the voltage curve, which becomes steady long before the first flat is reached. At the flats also there is less disturbance and the oscillations quickly die down. The performance is distinctly superior to that given by the radial brush.

Subsequently comparative tests were made with a trailing brush with a bottom angle of 5° and a top angle of 13° (Fig. 2*f*) and a similar brush but with a bottom angle of 15°. These showed a negligible difference in performance.

Reaction Brush.—Coming to the reaction brush, it will be noticed that the entering side loses its current momentarily only, due to tilting. The leaving side breaks for two or three segments and the oscillations persist over about ten segments. Conditions are then stable until the first flat is reached. The high-frequency ripple shown, corresponds to segment frequency. The voltage curve over the smooth part of the commutator is extremely uniform. The performance with the reaction brush in these three tests is definitely superior to that given by both the radial and trailing brushes.

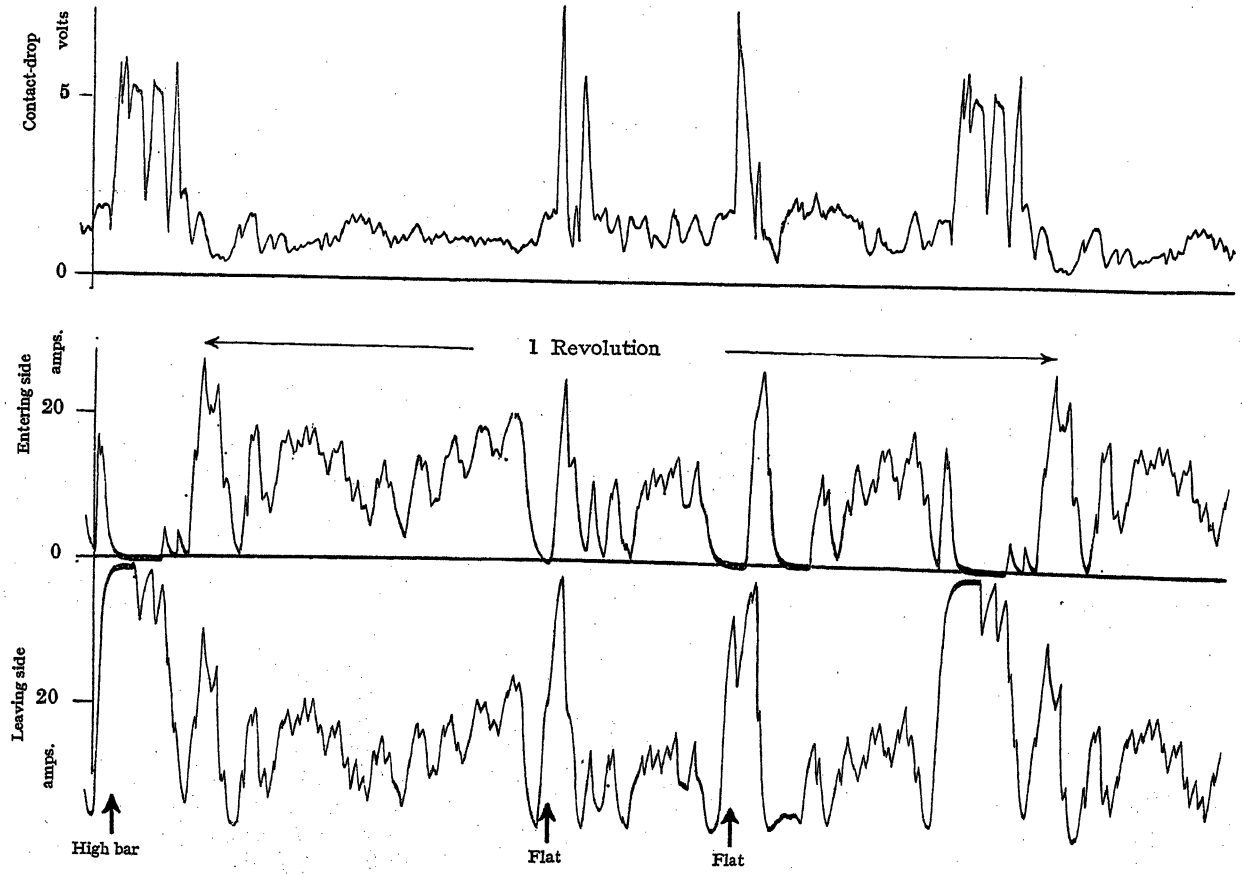


FIG. 5.—Contact-drop and current in each half of 15° trailing brush, diagonal in holder.

As mentioned under the heading of "Reversible Running," an experiment was made with the bottom bevel reduced to 20° (Fig. 2*p*), but the behaviour was very unstable in the reaction direction.

Radial versus Trailing.—The results of these three tests suggested that a further test should be made to demonstrate that the inferior performance of the radial brush was due purely to the fact that it was mounted radially, and not to some other feature. The contact surface was therefore bevelled slightly to make the brush run 5° trailing, the top being left square and the rib undisturbed. The holder was titled correspondingly. brush was tried. The brush used was as shown in Fig. 2(*h*), the holder similar to that in Fig. 1(*a*), and the results are shown in the oscillogram of Fig. 8.

Comparison of Fig. 8 with Fig. 5 shows an improvement due to the bevel. The disturbance is less and of shorter duration; the oscillations are less violent and are quickly damped out. The voltage curve also is smoother. In passing, it may be mentioned that with this arrangement of bevels, which causes the brush to bear against the leaving side of the box both at the top and at the bottom, the box should be relatively deep and it is necessary to make the angle of the top bevel

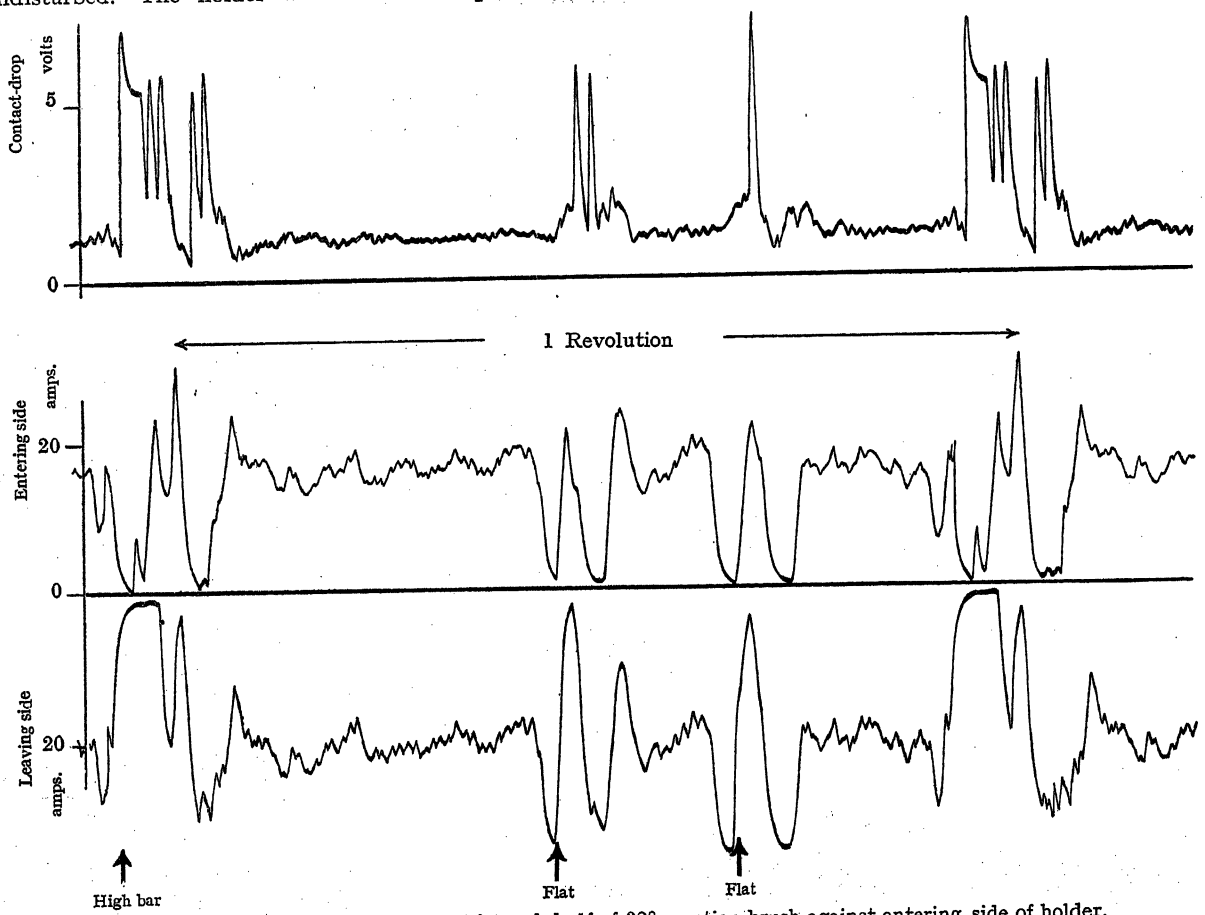


FIG. 6.—Contact-drop and current in each half of 32° reaction brush against entering side of holder.

The precaution was taken to leave the reaction brush undisturbed in order to prove that the commutator condition remained unchanged. The brush used was as shown in Fig. 2(*e*), the holder in Fig. 1(*a*), and the results are shown in the oscillogram of Fig. 7.

Comparison of Fig. 7 with Fig. 4 shows that a great improvement has been effected by altering the radial brush to 5° trailing. The disturbance at the high bar and flats is of much shorter duration and much less violent, whilst the voltage over the smooth part of the commutator is very uniform.

INFLUENCE OF TOP BEVEL.

Trailing Brush.—Concurrently with the above test, the effect of reversing the top bevel on the 15° trailing considerable, otherwise the side component of pressure will prove insufficient to hold the brush against the top of the box, even when running on the smooth part of the commutator. With the majority of machines the tendency is to adjust the commutating-pole strength so that the current density is greater on the entering side of the brush than the leaving, tending to cause greater wear and therefore imperfect contact on the entering side. In actual practice it has been found that an insufficient angle of top bevel has allowed individual brushes to tilt on to their entering edges, causing them to be severely overloaded and their flexible leads to be burnt out.

Reaction Brush.—In view of the diversity of practice with regard to the top angle of a reaction brush it was

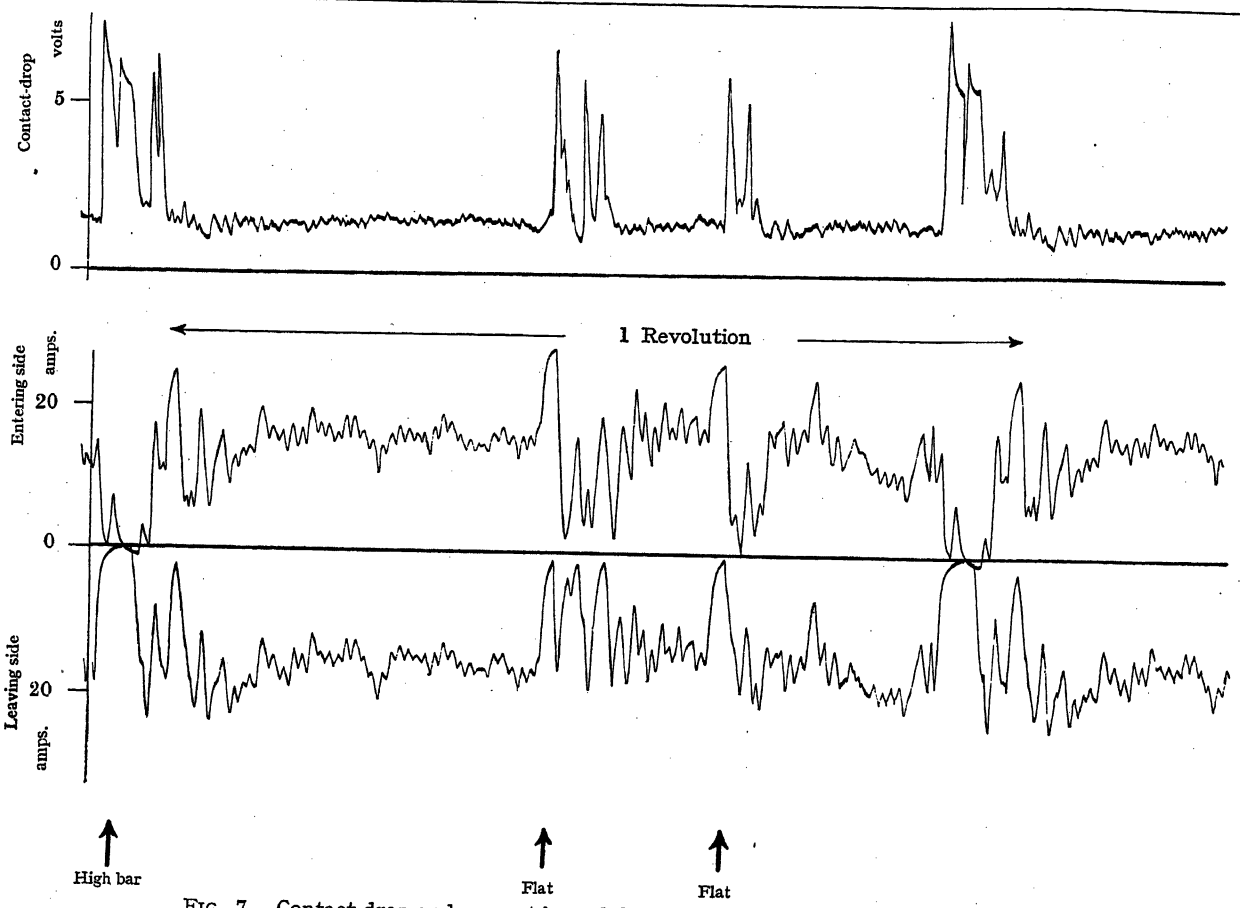


FIG. 7.—Contact-drop and current in each half of ribbed trailing brush with square top.

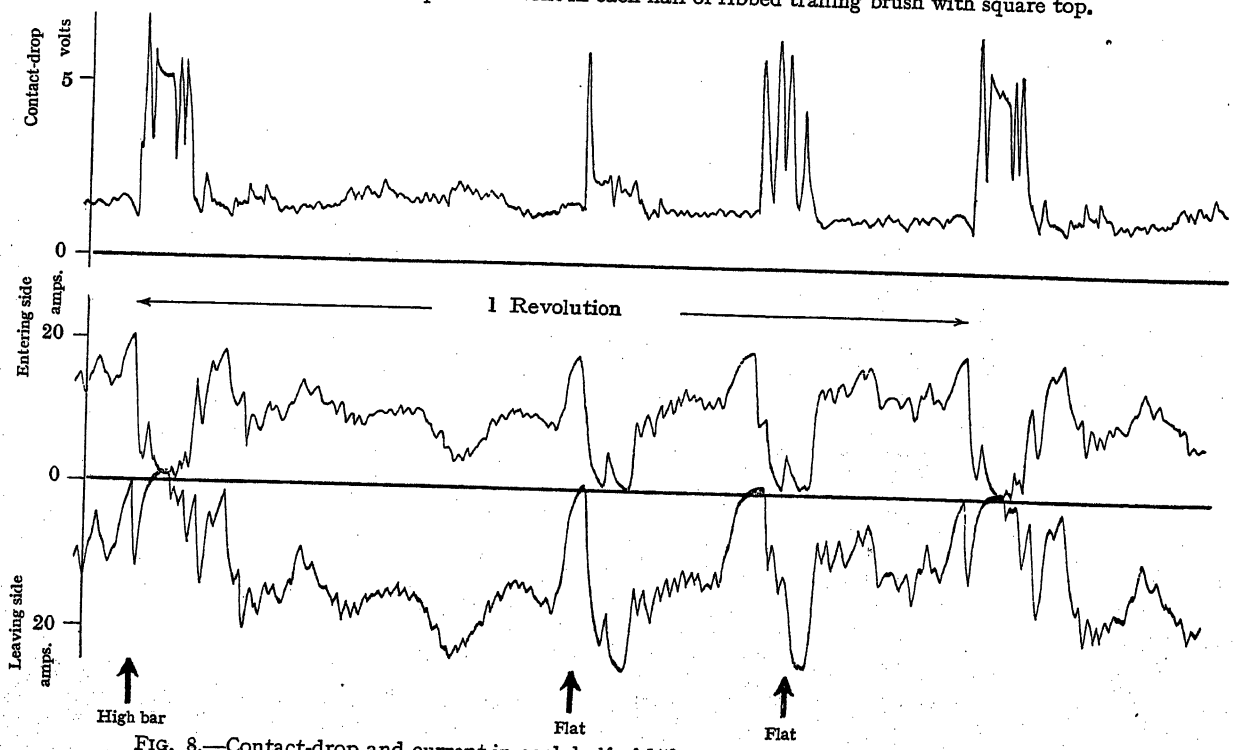


FIG. 8.—Contact-drop and current in each half of 15° trailing brush against leaving side of holder.

decided to investigate the influence of varying this. With a square top, i.e. no bevel (Fig. 2*m*), it was found that the current wandered about from one half of the brush to the other at approximately 5-minute intervals throughout the several days it was kept under observation. The oscillograms of Figs. 9 and 10 show the current uniformly distributed in the one case and entirely in the leaving half in the other. At other times the current was entirely in the entering half.

With a reversed top bevel of 13° (Fig. 2*n*) it was observed that the brush was extremely sensitive to the disturbing influence of flats and high bars. This caused in one or other half of the brush the concentration of the entire current, and this concentration was often maintained until the succeeding flat or high bar was reached.

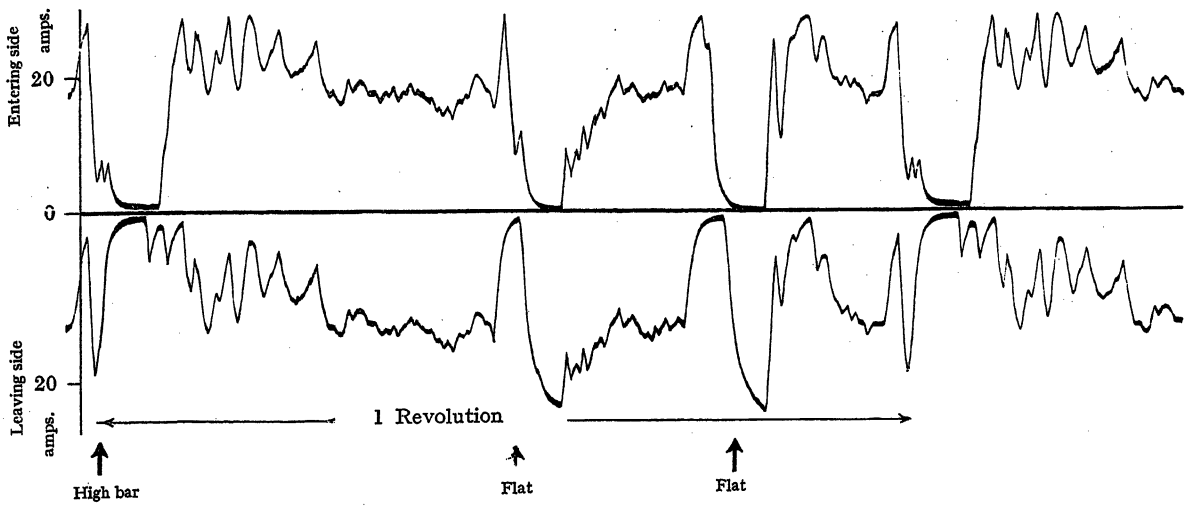


FIG. 9.—Current in each half of 32° reaction brush with square top.

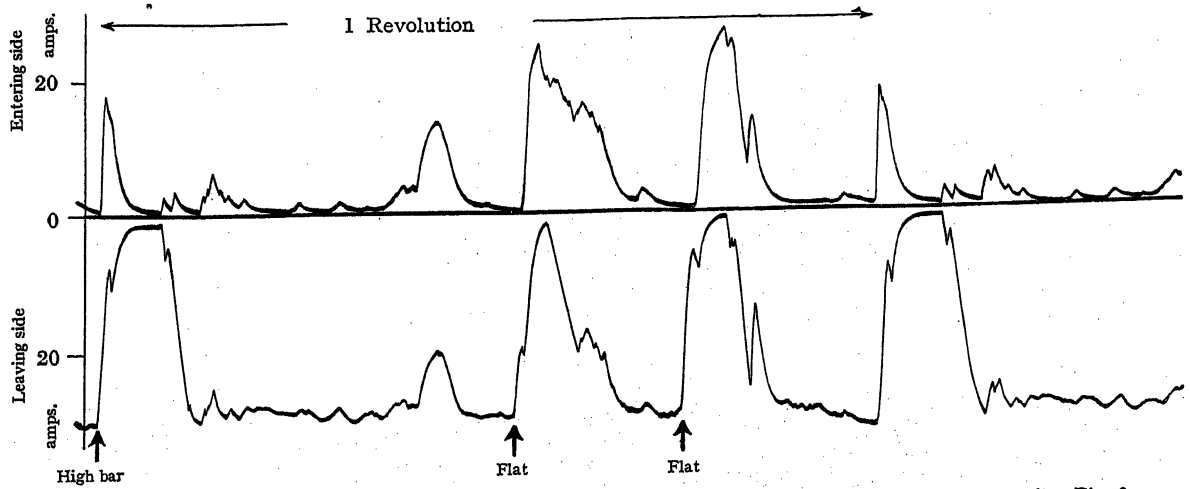


FIG. 10.—Current in each half of 32° reaction brush with square top. Recorded a few minutes after Fig. 9.

REVERSIBLE RUNNING.

In commercial practice some types of machines such as traction, crane, and rolling-mill motors have to reverse frequently. Furthermore, when ordinary industrial motors are made and put into stock it is seldom known in which direction they will ultimately be required to run. It therefore becomes important to observe the effect upon the behaviour of a brush when the direction of rotation is reversed. Examination of the oscillograms already referred to shows that the performance is better when the brush is held against one face of the box both top and bottom than when it lies diagonally in the box. In a reversible machine, however, this cannot be associated with a large angle of tilt because in one direction of rotation there is danger of developing excessive friction due to the increased pressure normal to the commutator, and in extreme cases with uneven commutators there is danger of a distinct wedging action in the holders. On the other hand, with ordinary designs of holders, if the angle is made small general experience demonstrates that the brushes do not run well reaction, because there is not sufficient force to

hold the brush securely against the box at the bottom. This is confirmed by the test made on the brushes shown in Figs. 2(*k*) and 2(*h*) and referred to below. The problem then is to design a brush and holder for reversible running which will show the superior performance of a reaction brush running in the normal direction without exhibiting the disadvantages of this brush when run in the reverse direction.

The direction of rotation of the machine was changed at frequent intervals immediately before each of the oscillograms in Figs. 11 to 16 was taken.

Cantilever Brush.—With the cantilever brush the direction of rotation is described as being "normal" when the rotation tends to carry the brush away from the face against which it is held by the pressure finger. Fig. 11 shows that with normal rotation the distribution

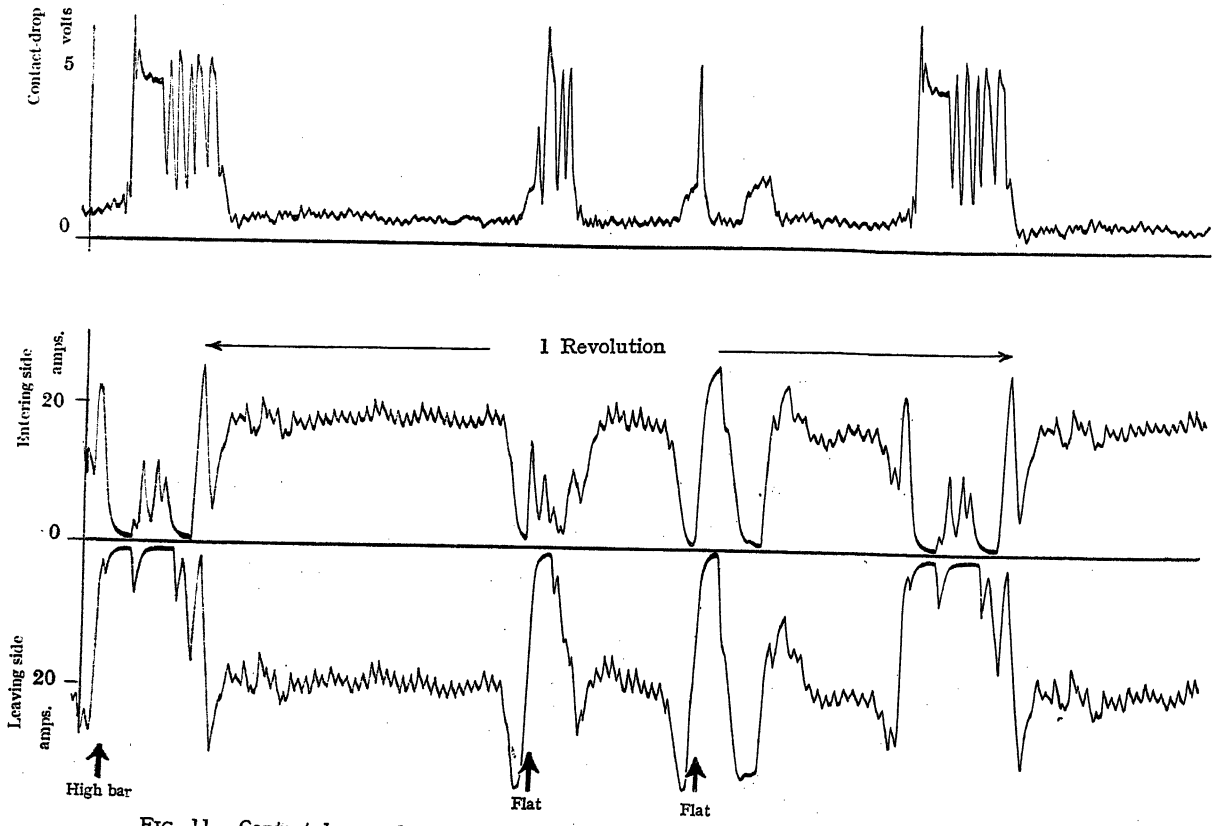


FIG. 11.—Contact-drop and current in each half of cantilever radial brush. Rotation normal.

Principle of Cantilever Radial Brush.—Consideration of the principles referred to led to the development of what is herein referred to as a cantilever type of brush, Fig. 2(*d*). This brush is set radially to the commutator and is provided with an overhanging metal top against which the pressure finger bears in such a way as to give a component of pressure which will hold the brush against one face of the brush box, irrespective of the direction of rotation. This design obviates the disadvantages of a tilted brush on a reversible machine, whilst the advantages of damping the brush by holding it against one face of the box are secured. Brushes of this type on an ordinary industrial reversing motor operating under severe conditions have been kept under observation for several months. The behaviour has been entirely satisfactory. Noisy operation and the development of a double contact surface previously experienced with an ordinary radial holder and the same grade of brush have been completely eliminated. A cantilever brush was used in the experiments now to be described and referred to in Table 2.

of current between the two halves is quite good, but the disturbance at the high bar is of rather long duration.

TABLE 2.

Brush		Holder, Fig. No.	Oscillogram, Fig. No.	
Description	Fig. No.		Normal rotation	Reversed rotation
Cantilever radial	2(*d*)	1(*e*)	11	12
Trailing 15°, 13° reversed top bevel	2(*h*)	Similar to 1(*a*)	13	14
Reaction 32°, 15° top bevel	2(*k*)	1(*g*)	15	16

With rotation reversed (Fig. 12) the general distribution between the two halves is again good, and after the high bar stability is quickly restored.

Trailing Brush.—It will be seen that the trailing brush has been upset by reversible running, and now with rotation normal (Fig. 13) the leaving side takes approximately 50 per cent more current than the entering side. When the rotation is reversed (Fig. 14) the distribution becomes still more unbalanced, the current on the leaving side being approximately four times that on the entering side. Also there are considerable fluctuations in contact resistance, as evidenced by the voltage curve. It will be realized, of course, that this trailing brush with reversed rotation becomes a reaction brush at a small angle.

Reaction Brush.—The performance with the reaction brush rotation normal (Fig. 15) is excellent. The distribution of current between the two halves of the brush is very uniform and the voltage curve very steady. The segment ripple is very clearly shown. With rotation reversed (Fig. 16) there are rather violent oscillations over the flats and high bar, but over the smooth part of the commutator the current is approximately equally divided and steady.

The contact-drop with reversed rotation (Fig. 16) is very low compared with that obtained with normal rotation (Fig. 15). This difference was evidently due to the wedging action with reversed rotation and, to investigate this, friction and contact-drop tests with an ordinary voltmeter were made. These revealed that the friction was no less than 62 per cent higher, and the mean contact-drop 37 per cent lower, with rotation reversed than with rotation normal. The heating resulting from the increased friction, and the disturbing effect upon commutation of a varying contact-drop, render this brush unsuitable for reversible running.

In view of this result it was decided to reduce the bottom bevel to 20° (Fig. 2*p*). This brush was kept under observation for four or five days, but showed periods of serious unbalance of current so that further tests with it were abandoned.

Stability of Arc of Contact.

Since commutation, as distinct from mere collection, is a time process, and since the strength of commutating poles is adjusted on the assumption that two adjacent segments will be short-circuited by the brushes for a definite period of time, it follows that it is a matter of vital importance for the arc of actual contact between brush and commutator to remain constant. As the next step it was therefore considered advisable to make up special brushes subdivided into four parts. The two outside sections were made equal to each other and half the thickness of the two inside sections, as indicated in Table 3.

It will be noticed that the distribution of current between the four parts of the brush is remarkably uniform in all three cases, the reaction brush being perhaps slightly the best, closely followed by the cantilever and the trailing in the order mentioned. It is considered that these oscillograms completely dispose

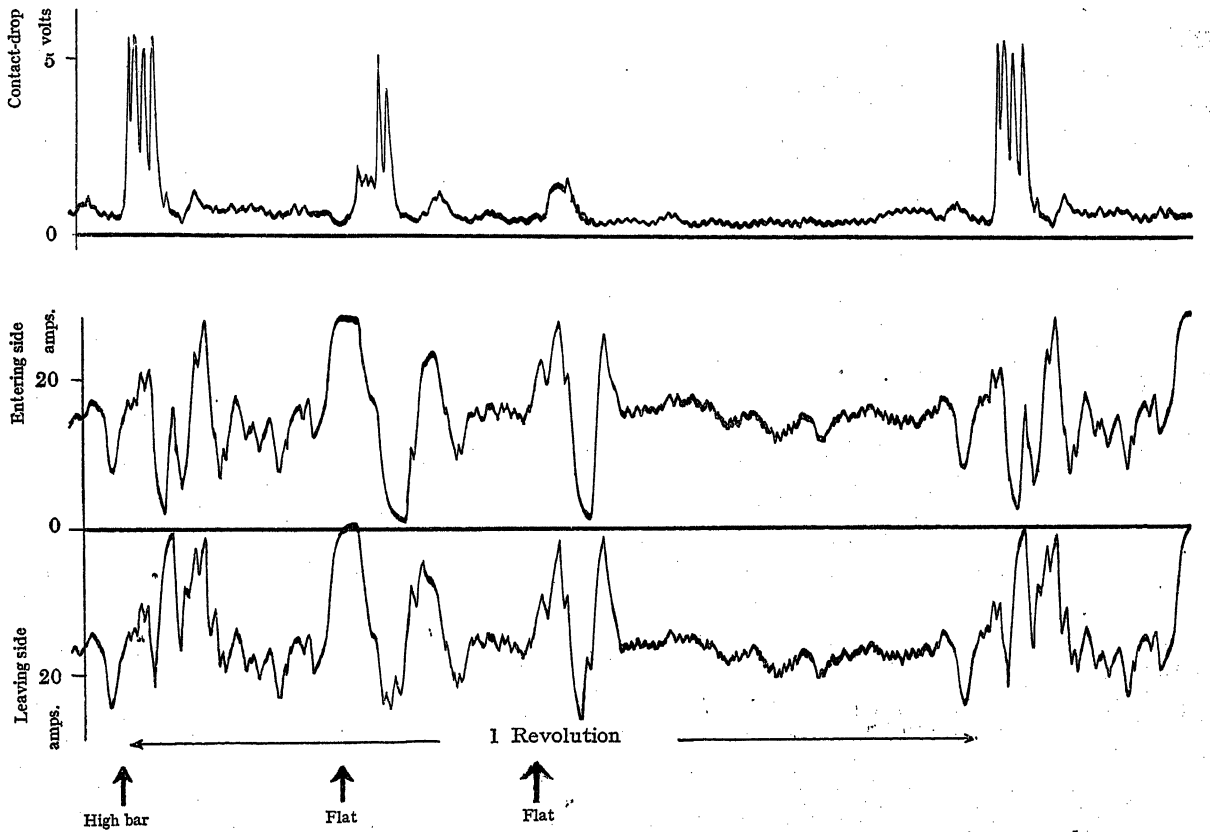


Fig. 12.—Contact-drop and current in each half of cantilever radial brush. Rotation reversed.

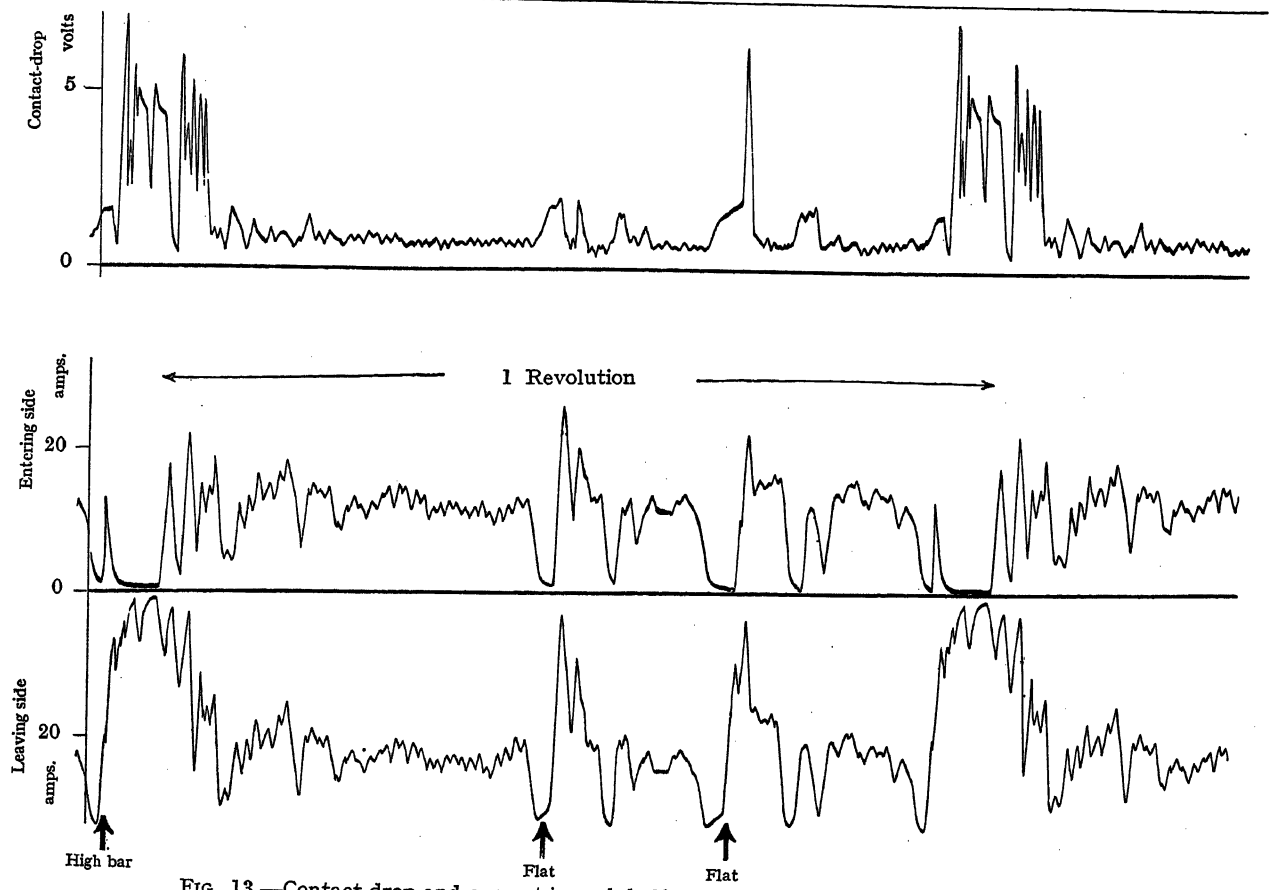


FIG. 13.—Contact-drop and current in each half of 15° trailing brush. Rotation normal.

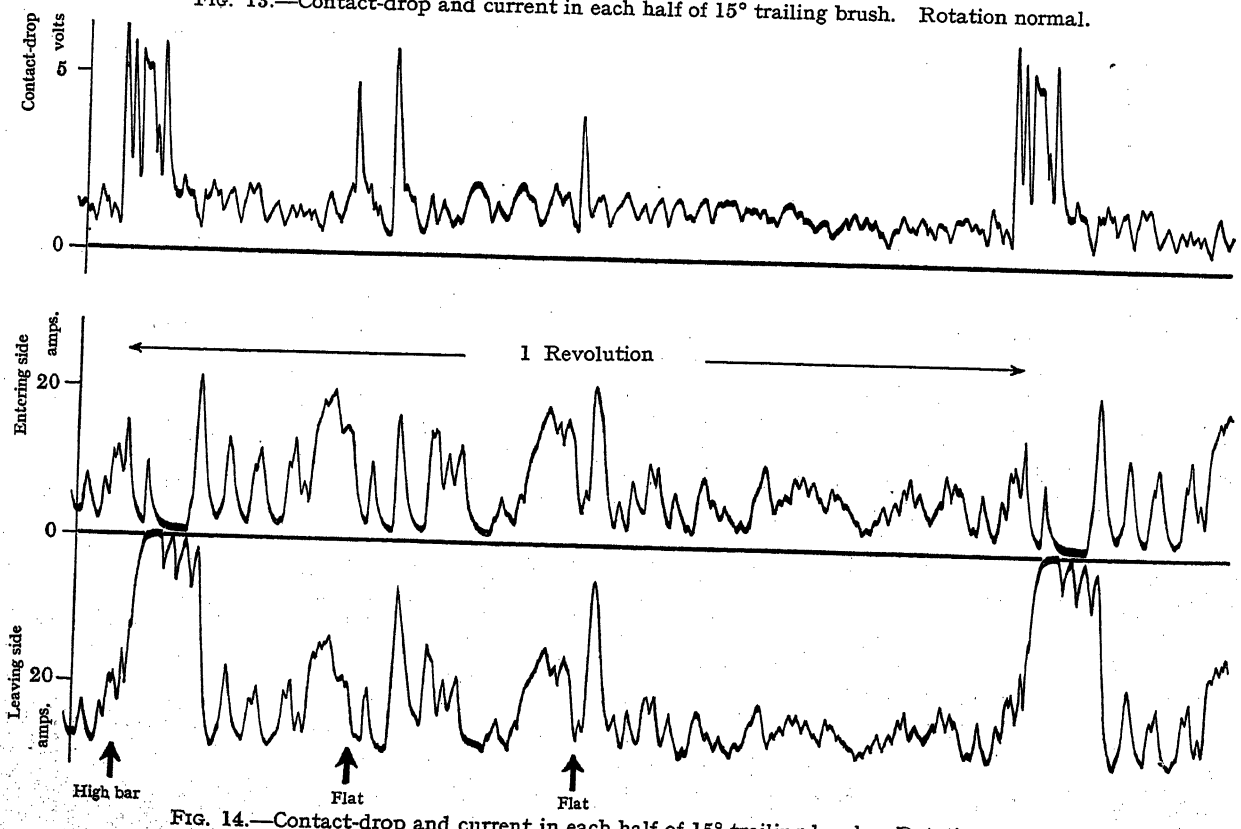


FIG. 14.—Contact-drop and current in each half of 15° trailing brush. Rotation reversed.

of the theory sometimes advanced that a brush makes contact with the commutator at three points only, a theory that is based on the false premise that the brush is inelastic. These oscillograms show not only that the brush is making contact at more than three points, but that contact must be made at a multiplicity of points, otherwise the distribution of current between the several parts of the brush could not be so nearly in proportion to the areas. Moreover, the distribution as shown by these oscillograms may be accepted as characteristic of the behaviour, since it was observed on the screen to persist for days together. Any brush could be removed from its holder and then replaced on the commutator without upsetting the distribution.

TABLE 3.

Four-Part Brush.

Description	Fig. No.	Holder, Fig. No.	Oscillogram, Fig. No.
Cantilever	2(*d*)	1(*e*)	17
Trailing 15°, 13° reversed top bevel	2(*h*)	Similar to 1(*a*)	18
Reaction 32°, 15° top bevel	2(*k*)	1(*g*)	19

In actual practice it is not infrequently observed that a machine will run quite sparklessly for a considerable period, perhaps several weeks. Gradually the machine may then begin to spark and eventually the sparking may become serious. If careful observation of the brush voltage curve is kept it will generally be found in these circumstances that the shape gradually changes. Sometimes the voltage rises to such a high value at one or other end of the curve that the reading can only be due to the combination of a rotational e.m.f. with the contact-drop, caused by imperfect contact across the face of the brush. The phenomenon described has been observed particularly on large machines by a variety of makers and with various kinds of brushes fitted, but notably has not been observed on machines equipped with double brush gear, that is to say, with two brushes in each holder, one in front of the other. It is considered that this phenomenon is due to the arc of contact between a single brush and commutator changing in the course of time. The next step in these tests was therefore to investigate whether the distribution of current could be more easily upset with one design of brush than with another. To cause a disturbance the speed of the plant was increased from 6 000 to 8 900 ft. per min. In the case of the reaction brush, in less than

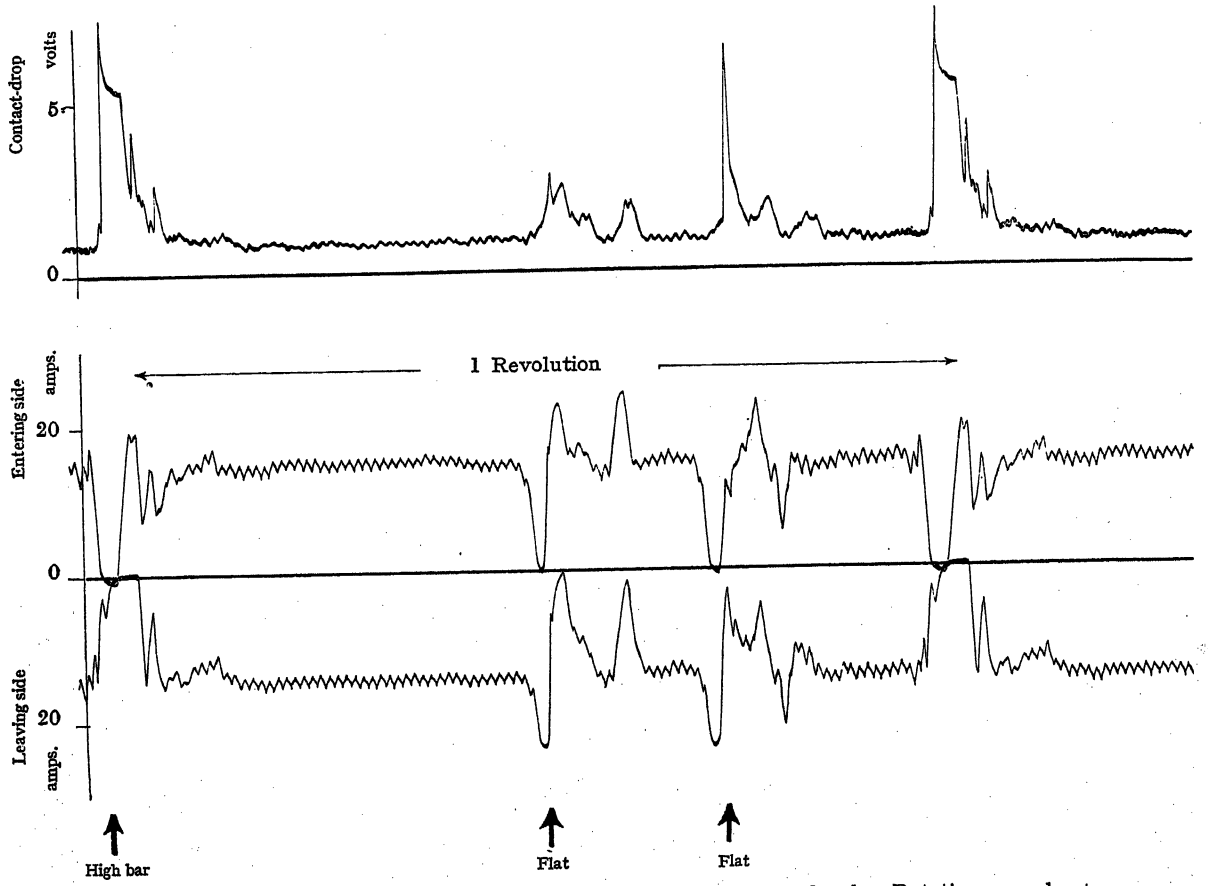


FIG. 15.—Contact-drop and current in each half of 32° reaction brush. Rotation normal.

5 minutes approximately the whole of the current was carried by the entering half of the brush. When the speed was reduced the brush recovered itself at once and the distribution of current became even. This cycle could be repeated as often as desired, always with the same results. The cantilever and trailing brushes remained practically unaffected when the speed was changed in the same way, the cantilever brush proving to be even more stable than the trailing brush.

To confirm that the behaviour of the reaction brush was attributable to the reaction angle and not to the particular design of holder, a second reaction brush-holder of the design illustrated in Fig. 1(*f*) was mounted in place of the cantilever holder. When the speed was raised from 6 000 to 8 900 ft. per min. it was observed that the current-sharing between the two halves of both reaction brushes was similar and very erratic, the current tending to concentrate in the entering side. The trailing brush remained practically unaffected. On the speed being reduced to 6 000 ft. per min. uniform current-sharing was immediately restored. The speed was next dropped below 6 000 ft. per min., but this had no effect upon the distribution of current.

To confirm the theory that the disturbance in the arc of contact was due to the reaction brushes taking up new positions in their holders and not to mere vibration, both these brushes were allowed to run at the high speed for 24 hours. Observation on the current in each of the four sections of both brushes was made at frequent intervals and showed during the first three or four hours that the whole of the current, with the exception of peaks corresponding to the high bars and flats, was confined to the two entering sections. Gradually, however, the current crept into the third section and within 24 hours became uniformly distributed. It was evident, therefore, that the brush had changed its arc of contact with the commutator.

The movement of the brush in its box was at first thought to be due to a change in the frictional force, but observations made on the dynamometer gear definitely established that the coefficient of friction remained unchanged. It was next thought that an increase of temperature resulting from the increased speed was responsible, but when the commutator was heated several times by applying wood blocks to the part free from brushes the result was uncertain. Sometimes the current wandered to one side and sometimes merely showed a tendency to become unstable. Since the disturbing effect of an increase in temperature was not due to a change in the frictional force it was felt that it must be due to the slight increase in the diameter of the commutator. Tests were therefore made to measure this and it was found to amount to approximately 0·0012 in. for the increase in temperature which had caused the disturbance. Similar tests were then made on a cold commutator, first at 6 000 ft. per min. and then at 8 900 ft. per min., and it was found that an increase in diameter amounting to approximately 0·005 in.

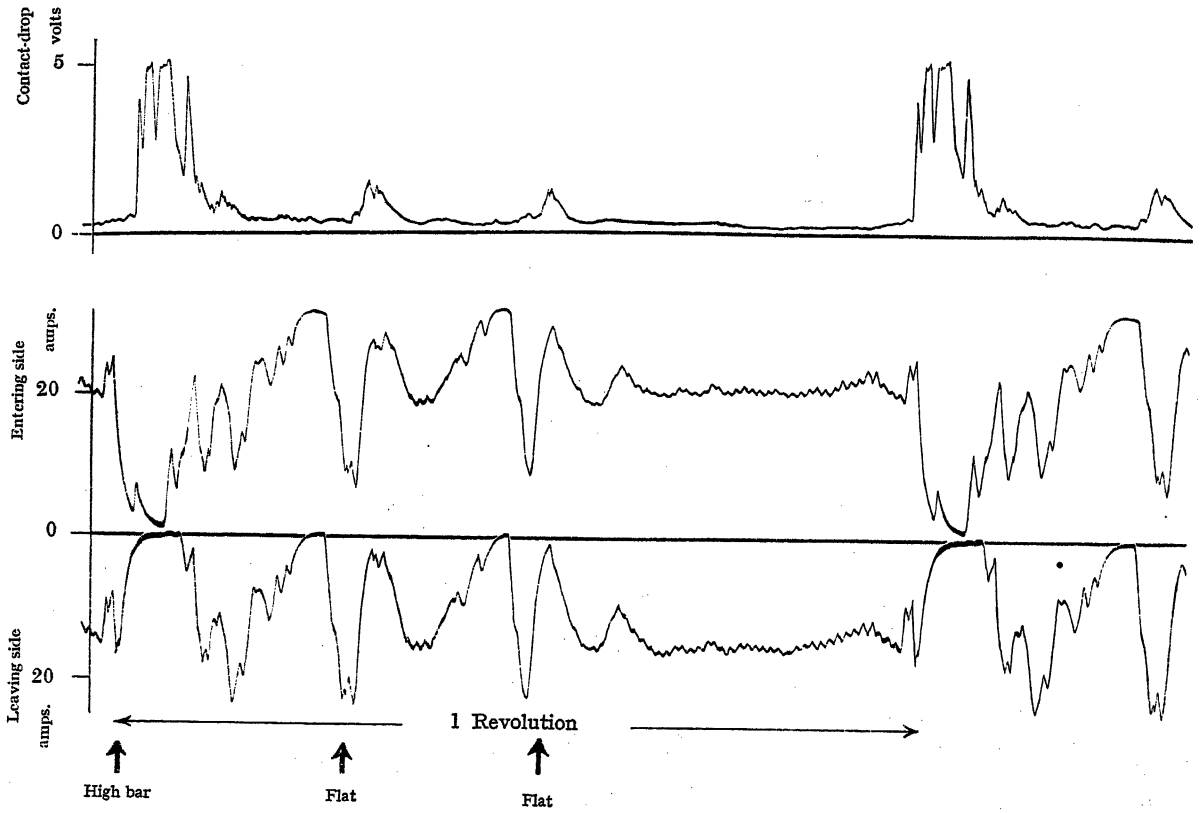


FIG. 16.—Contact-drop and current in each half of 32° reaction brush. Rotation reversed.

occurred at the latter speed. With a radial brush the error introduced in the radius of the contact surface when the commutator diameter is increased by 0·005 in. is so small as to be taken care of by the elasticity of the brush. When, however, a reaction brush is tilted at a considerable angle it is apparent from an inspection of Fig. 20 that the brush tends to break contact at the leaving edge so long as it maintains contact with the same face of the box. With only a reasonable expansion

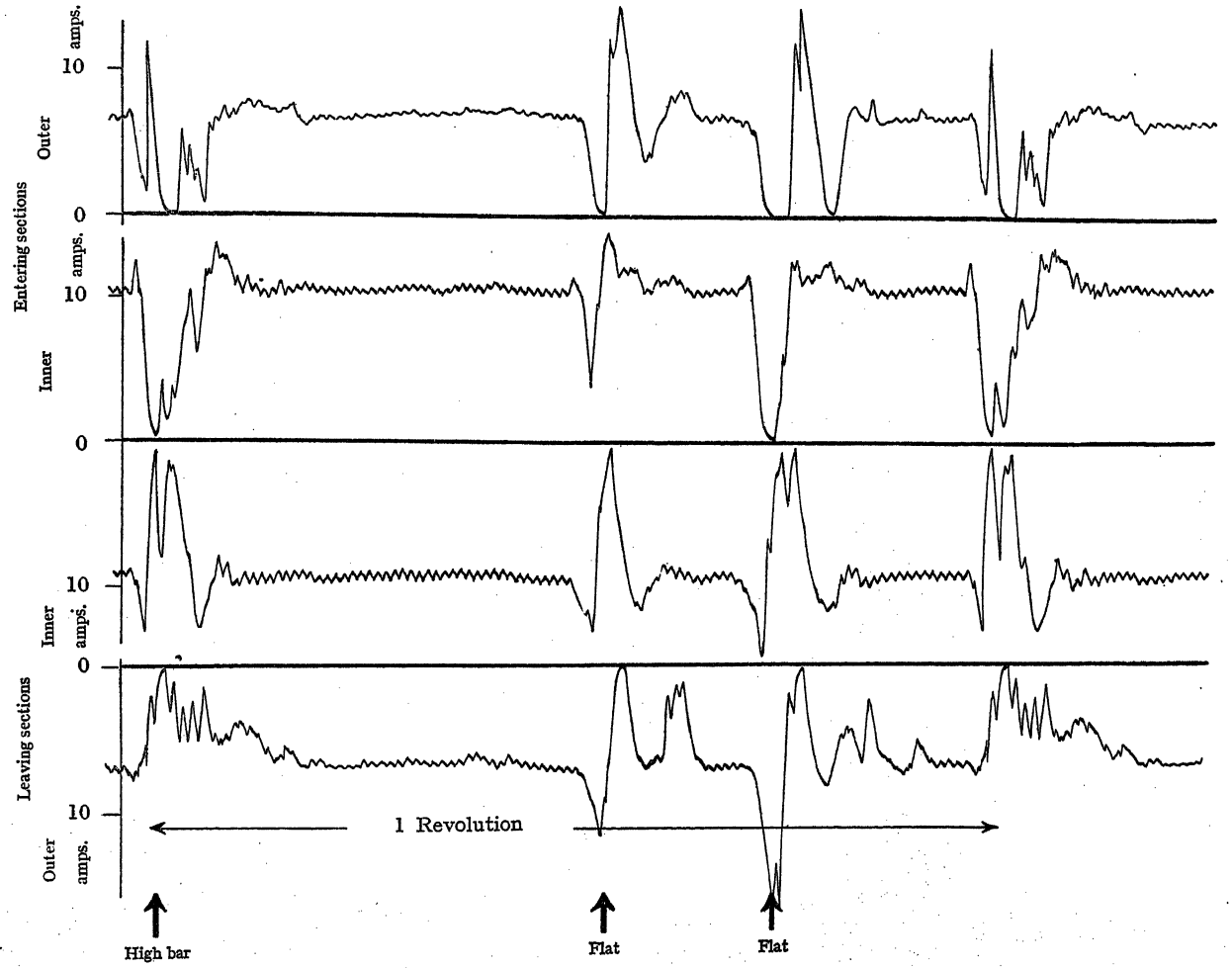


FIG. 17.—Current in each section of 4-part cantilever radial brush.

combined with an angle as large as 30° the elasticity is insufficient to ensure a perfect contact.

The change produced by raising the speed in the test described could be produced in practice by a number of causes such as the following:—Eccentricity of the commutator; out-of-balance; a change of position of the armature shaft in its bearing; a movement of brush arms; changes of temperature due to changes of load; variations in centrifugal force (in variable-speed machines). Irregularities such as these may be described as "gradual," as distinct from "sudden" irregularities, such as high bars or flats.

It thus appears that the cantilever brush is definitely the best of those tested for reversible work. It is also very good for running in one direction only, but in common with all the others is badly upset by a high bar. The effect would be reduced if double brush gear were used, i.e. one brush in front of the other circumferentially, free to move independently of each other. This arrangement is hereinafter referred to as "tandem."

Comparing the slightly trailing brush with the reaction brush, the latter is inferior in maintaining the arc of contact when the irregularity is of the "gradual" type but this defect can be minimized by the use of tandem gear. The reaction brush, however, is distinctly superior when the defect takes the form of a "sudden" irregularity such as a high bar or flat. This may explain to some extent the diversity of practice amongst machine constructors as regards trailing and reaction running.

The tests suggest that greater benefit is derived from the use of tandem brush gear with reaction running than trailing running, although the use of this gear must in all cases tend to stabilize the arc of contact.

ALTERNATIVE TO TANDEM GEAR.

The use of tandem brushes imposes serious restrictions upon the design of the holders. The query arises

whether it is possible to secure the advantages offered by them without encountering the limitations referred to.

Before attempting to answer this query it is necessary to appreciate the influence of current density upon brush operation.

The very common practice of thinking in terms of current density in a brush (i.e. amps. per sq. in. of contact surface) is sometimes criticized on the score that contact resistance is not affected by size of brush, provided the total pressure is kept constant. The current density, however, affords a very useful rough indication of the rate of wear that may be expected—obviously a matter of first importance.

the current density. This increases the contact-drop and therefore the total I^2R loss, but the friction would be halved and it is probable that the net result would be a decrease in the total commutator loss, so that no increase in size of commutator would be necessary. With this arrangement the rate of wear would be increased because removing half the brushes halves the number of points of contact available. Since the number of brushes has been halved, however, the rate of wear can double before the brush consumption is increased. Probably an improved result would be obtained by increasing the pressure somewhat, as the *actual* density would thereby be decreased because carbon brushes are not perfectly

SUMMARY OF CONCLUSIONS.

Type of brush	Fig. No.	Stability as affected by "sudden" commutator irregularities	Constancy of arc of contact as affected by "gradual" commutator irregularities	Suitability for reversible running
Ordinary radial	2(*a*) and 2(*b*)	Very sensitive	Excellent	Tilts in its box, therefore bad
Ribbed radial	2(*c*)	Better than ordinary radial but not good	As 2(*a*) and 2(*b*) above	As 2(*a*) and 2(*b*) above
Cantilever radial	2(*d*)	Good	Excellent	Excellent
*Ribbed, trailing 5°, square top	2(*e*)	Great improvement over 2(*c*) above	Very good	Very bad
Trailing 5°, non-diagonal	2(*f*)	Very good	Very good, but very slightly inferior to 2(*d*) above	Bad
Trailing 15°, diagonal	2(*g*)	Superior to radial but inferior to 2(*h*) below	—	—
Trailing 15°, non-diagonal	2(*h*)	Very good	Very good, but slightly inferior to 2(*d*) above	Bad
Reaction 32°, non-diagonal	2(*k*)	Excellent	Easily upset	Wedging seriously affects friction and contact-drop
Reaction 32°, square top	2(*m*)	Definitely inferior to 2(*k*) above	—	—
Reaction 32°, diagonal	2(*n*)	Definitely inferior to 2(*k*) above	—	—
Reaction 20°, non-diagonal	2(*p*)	Very changeable and definitely inferior to 2(*k*) above	—	—

* Its practical equivalent in the form of a shallow box introduces risk of side wear.

Under a given total pressure the current per brush determines the rate at which the points of actual contact are consumed. It follows, therefore, that when the current is large the number of reserve points should be large, otherwise the rate of wear will be excessive. In other words, an excessive nominal current density is productive of a high rate of wear.

Tandem brushes assist in preserving the arc of contact and accordingly the time in which commutation must be effected. To secure this advantage with single brushes it is suggested that an arrangement might be developed whereby the brush thickness would be made equal to half the desired arc of contact, and alternate brushes would be staggered so as to cover the complete arc. Reverting to single brushes would immediately free the hands of the designer but at the cost of doubling rigid; also with increased pressure a greater force would be available for returning the brush quickly to the commutator when contact with the latter is broken, due to the presence of a flat or high bar.

A further improvement would be effected by reducing the width of the brush (provided this was not already as small as is practicable) and correspondingly increasing the number of brushes. This procedure would increase the actual area of contact with the commutator. This is very important from the commutation point of view as the brushes would then be operating on a less "saturated" portion of the contact-drop curve. To take a concrete case, imagine a machine to be fitted with 10 pairs of brushes per spindle, each brush $1\frac{1}{4}$ in. $\times$ $\frac{5}{8}$ in., and the full-load current density to be 55 amps. per sq. in. Assume the pressure to be $2\frac{1}{2}$ lb. per sq. in. and

peripheral speed 5 000 ft. per min. A mean contact-drop of 1·2 volts at this density and a coefficient of friction of 0·15 would be reasonable figures to assume. The loss per spindle would then be

I^2R loss	=	620 watts
Frictional loss	=	400 watts
Total ..		1 020 watts

Thus the alterations made have decreased rather than increased the total loss. Single brushes have been used: this gives the designer the maximum freedom in the design of the holder, whilst the advantage of tandem holders is retained so far as helping to preserve the full arc of contact is concerned. The nominal current density has been doubled, but as the total number of brushes has not been reduced by as much as one-half, the actual current density will not have been increased as much as the apparent density. In other words the actual current per brush has not been increased from 26 amperes to 52 but to 37 only, and the lower the current per brush the better for commutation. The brush constitutes a small unit with a correspondingly large radiating surface, and is not small enough to introduce difficulties in providing it with an adequate flexible lead.

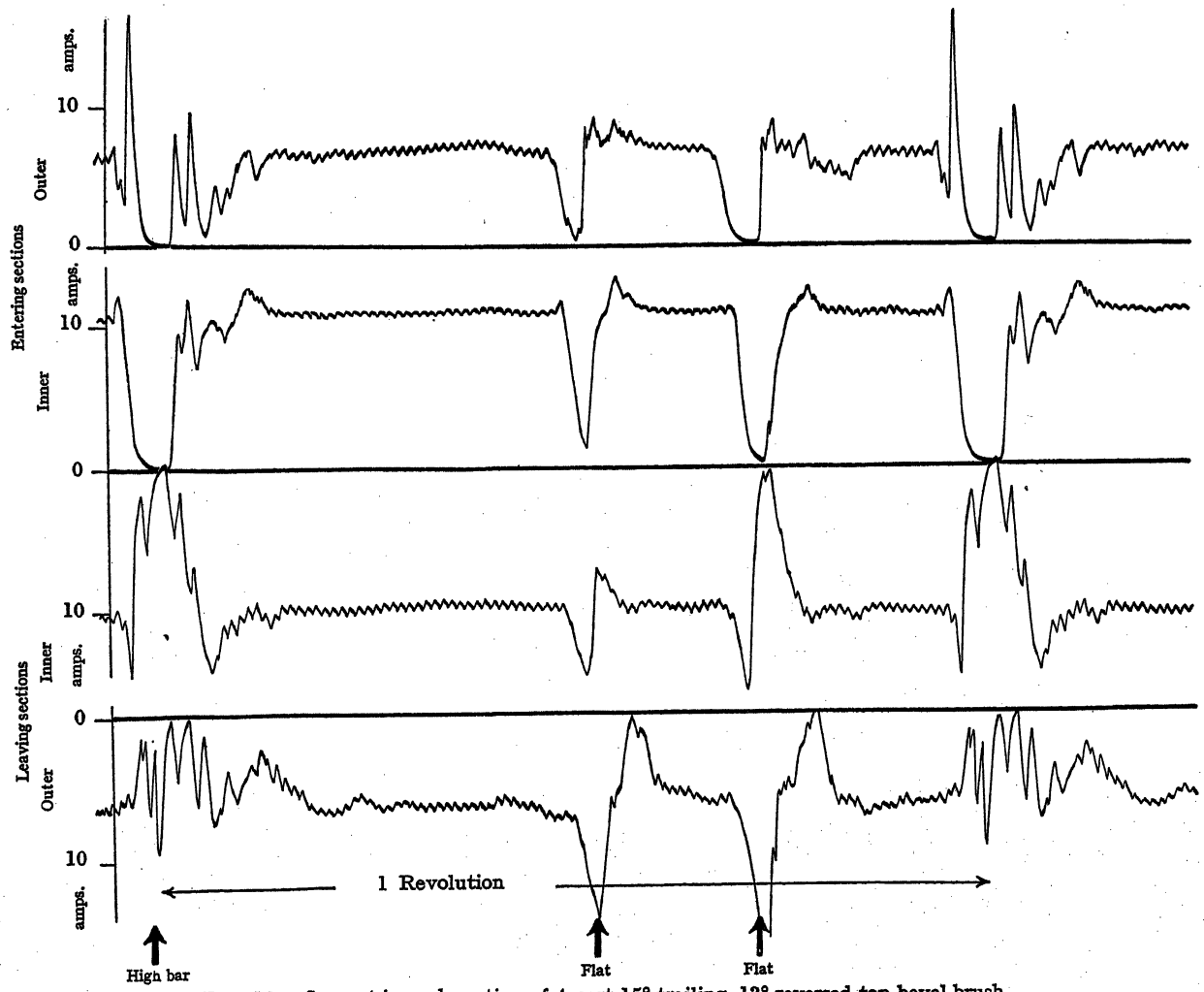


FIG. 18.—Current in each section of 4-part 15° trailing, 13° reversed top bevel brush.

Now suppose 14 single brushes $\frac{7}{8}$ in. × $\frac{3}{8}$ in. be substituted, staggered to cover an arc of $\frac{3}{4}$ in. The current density will be 112 amps. per sq. in. A reasonable contact-drop at this density and at $2\frac{1}{2}$ lb. per sq. in. would be 1·4 volts. If a pressure of $3\frac{1}{2}$ lb. per sq. in. were applied this figure would be reduced to about 1·25 volts and the coefficient of friction increased to, say, 0·17. The loss per spindle would then be

I^2R loss	=	645 watts
Frictional loss	=	310 watts
Total ..		955 watts

An actual experiment upon these lines has been made upon a small machine. The brushes were first run at 50 amps. per sq. in. Brushes of half the thickness were then substituted and staggered along the spindles to cover the same arc of contact. It was not practicable

to increase the number of the brushes and reduce the width, as the latter was already small. With the nominal density doubled, the rate of wear increased

mising that it is considered that a further experiment along these lines with a larger machine would be fully warranted.

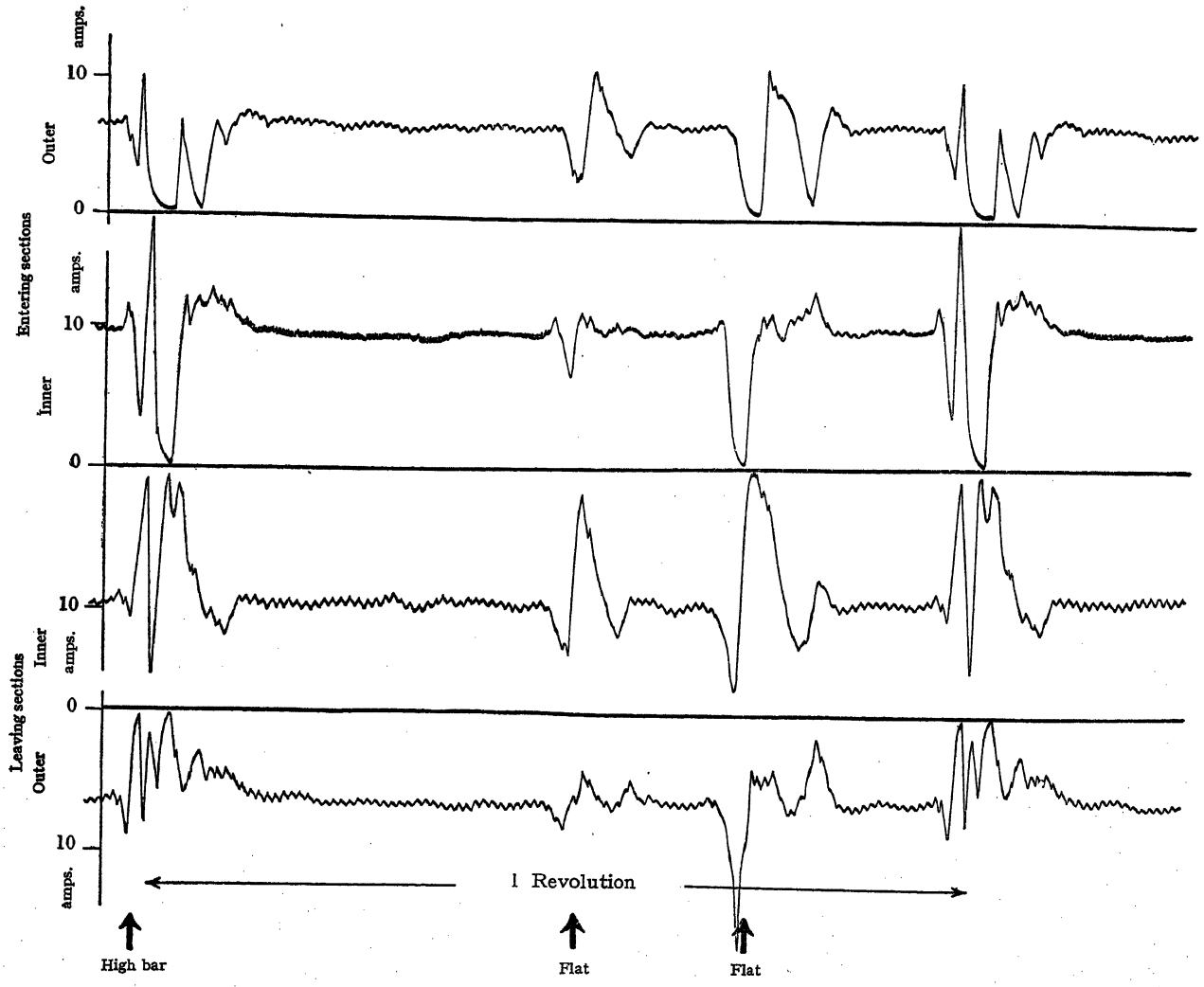


FIG. 19.—Current in each section of 4-part 32° reaction, 15° top bevel brush.

less than proportionally, so that the actual brush consumption was less than before. Commutation was

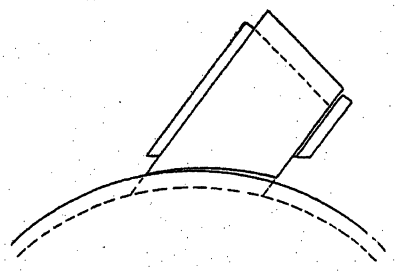


FIG. 20.—Effect (exaggerated) of a brush mounted on an eccentric commutator.

not quite so good, due to working higher up on the contact-drop curve, but the experiment was so pro-

TYPE OF PRESSURE FINGER AND SPRING.

It remains to consider the influence of inertia in the brush and pressure finger upon operation. Tests were made with four different pressure-finger designs. These are illustrated in Fig. 1 and embody (*a*) a clock spring, (*b*) a solid brass lever arm with helical spring, (*c*) as (*b*) but provided with an auxiliary spring tip, (*d*) plain helical compression spring with central guide stem. A holder was so constructed that the pressure gear could be changed without disturbing the holder on its spindle or the brush in its box. Running tests were made with each gear in turn on the commutator in the condition previously described. The results are shown in Figs. 21–24. The clockspring type shows a much longer disturbance and is definitely the worst of the four. The plain helical compression spring is next in order of demerit, whilst it is difficult to decide between the

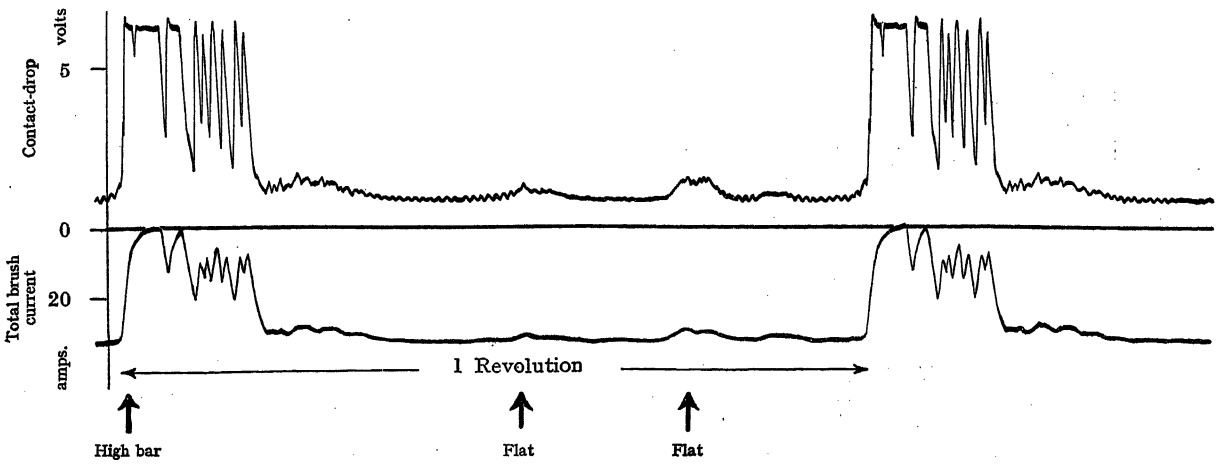


FIG. 21.—Brush contact-drop and current. Pressure applied with clock-type spring.

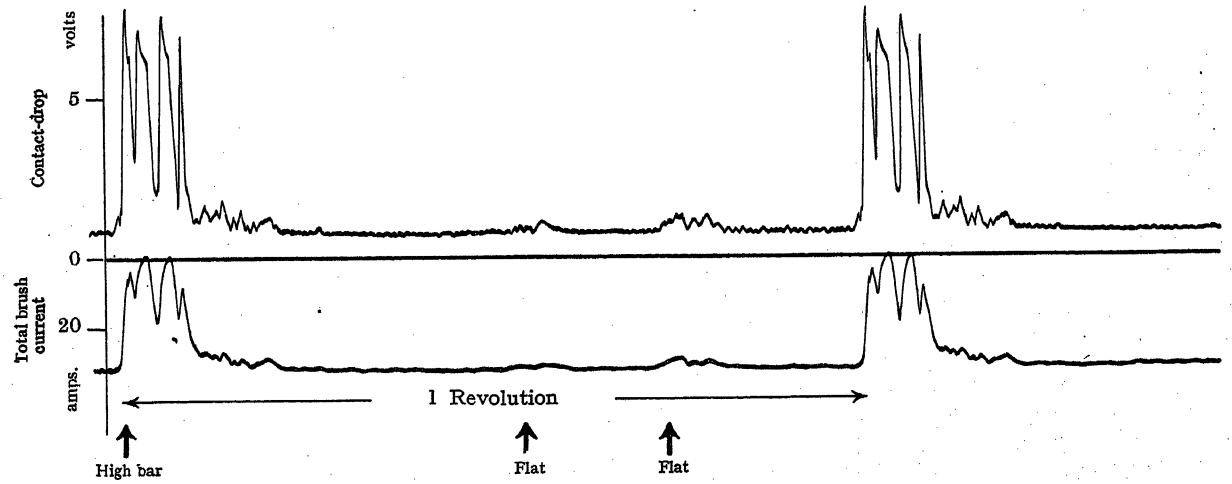


FIG. 22.—Brush contact-drop and current. Pressure applied with solid lever arm.

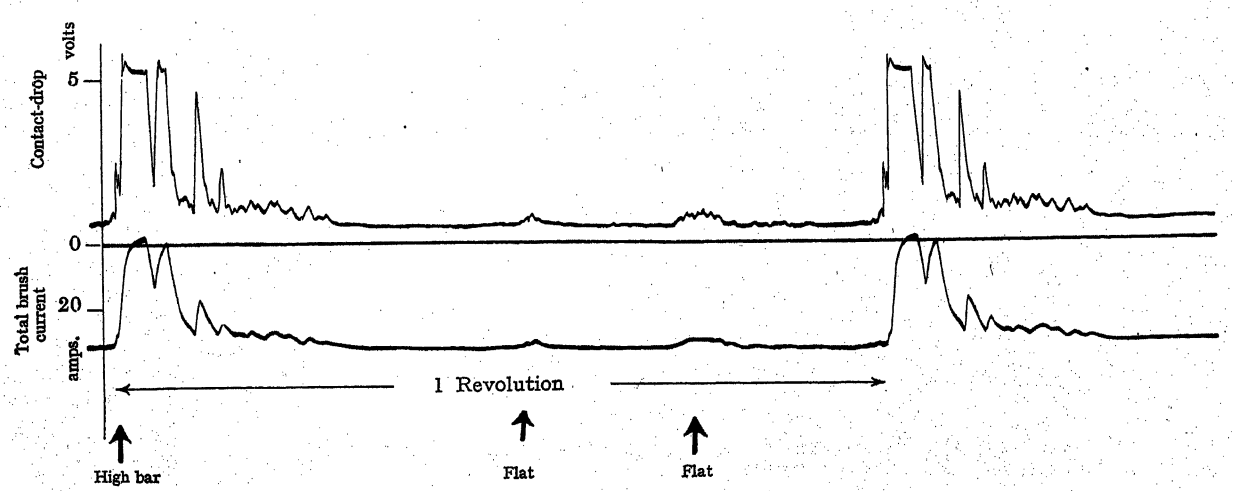


FIG. 23.—Brush contact-drop and current. Pressure applied with auxiliary light spring finger on lever arm.

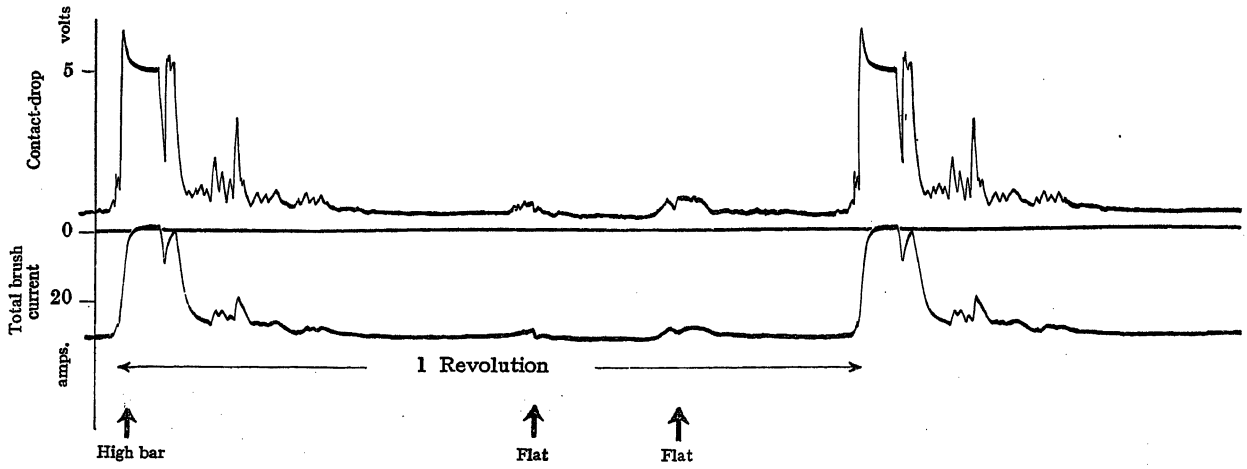


FIG. 24.—Brush contact-drop and current. Pressure applied with compressed helical spring.

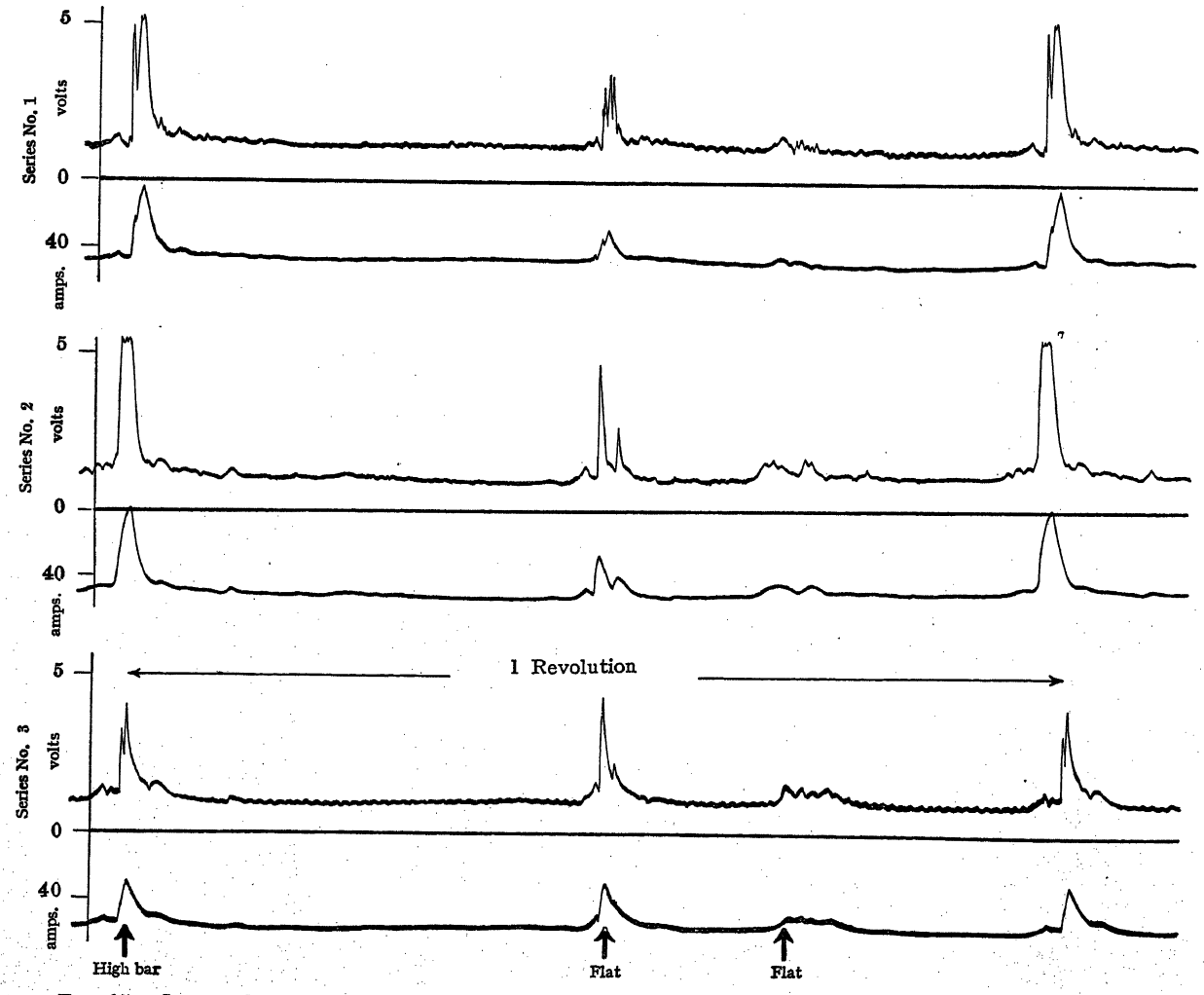


FIG. 25.—Contact-drop and brush current at 4 600 ft. per min. with varied inertia in the brush or pressure finger.

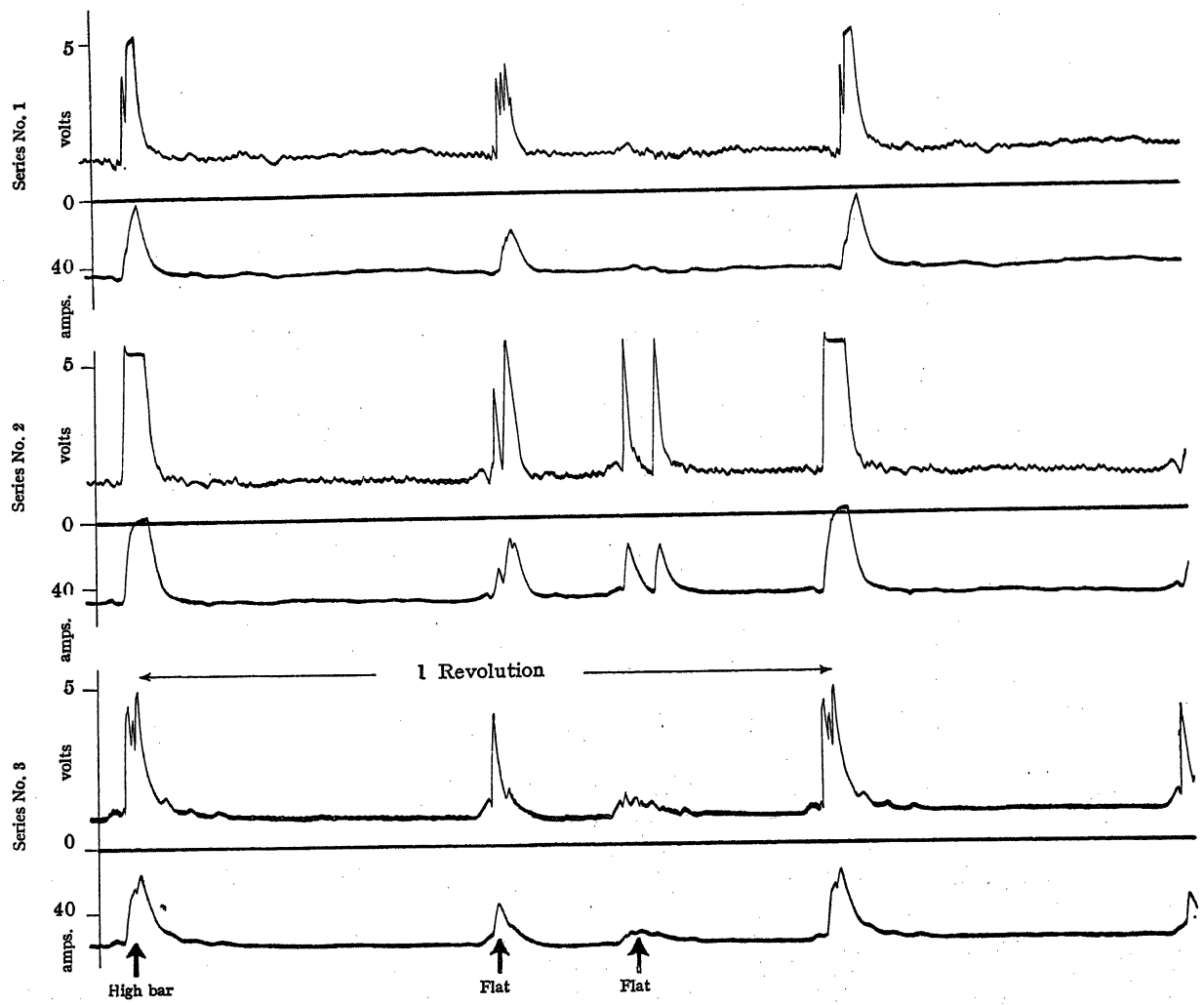


FIG. 26.—Contact-drop and brush current at 6 000 ft. per min. with varied inertia in the brush or pressure finger.

lever arm and the same arm modified to take an auxiliary light spring-tip.

The opinion usually held is that the addition of an auxiliary light spring-tip is beneficial, and in view of the comparative results shown in Figs. 22 and 23 further tests were made to investigate the effects of inertia.

A holder similar to Fig. 1(*a*) was selected for the test. In Table 4 " light finger " indicates the finger as illustrated. " Heavy finger " indicates the same finger with the addition of 36·5 grammes of lead folded around the lifting pin, which is immediately over the brush.

The brush was run 15° trailing with 13° reversed top bevel (see Fig. 2*h*). " Light brush " indicates that the brush was slotted as shown dotted and weighed 23·1 grammes. " Heavy brush " indicates that the slots were filled with 36·5 grammes of lead, making the total weight of the brush 59·6 grammes, equivalent to increasing the mean brush length (so far as weight is concerned) from 26 mm to 67 mm.

The group of tests shown in Table 4 was made.

In the first two series, as would be expected, an increase of speed is accompanied by an increase in the interval between the brush leaving and rejoining the commutator; also there is an increased disturbance at the flats. Comparing the light and heavy brushes at

TABLE 4.

Series	Finger	Brush	Speed		Oscillogram, Fig. No.
			r.p.m.	ft. per min.	
1	Light	Light	1 770	4 600	25
	Light	Light	2 300	6 000	26
	Light	Light	3 700	9 700	27
2	Light	Heavy	1 770	4 600	25
	Light	Heavy	2 300	6 000	26
	Light	Heavy	3 700	9 700	27
3	Heavy	Light	1 770	4 600	25
	Heavy	Light	2 300	6 000	26
	Heavy	Light	3 700	9 700	27

approximately the same speeds and with the same light finger, the detrimental effect of high *brush* inertia is apparent in each case.

in Series 1 be compared with those in Series 3, it will be noticed that the heavy pressure finger is better than the light one. The current is never broken at any speed

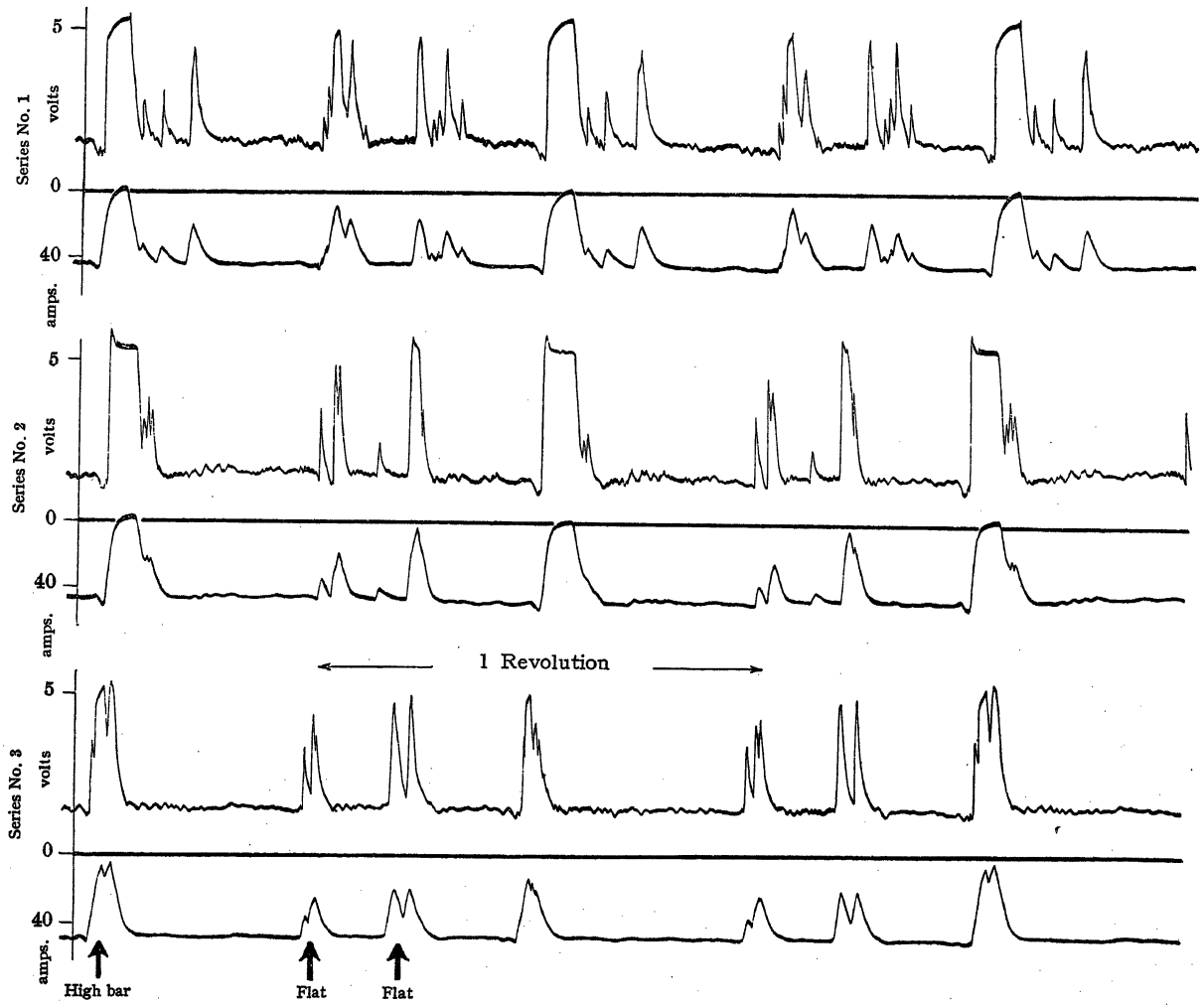


FIG. 27.—Contact-drop and brush current at 9 700 ft. per min. with varied inertia in the brush or pressure finger.

The effect of transferring the inertia from the brush to the finger is most interesting, as will be seen on comparing Series 2 with Series 3. The complete interruptions of current observed in Series 2 at each of the three speeds do not occur with Series 3. Further, the disturbance at the flats is small in the latter series. If the oscillograms with the heavy finger, and the difference in behaviour is most marked at the highest speed.

These results open up a fresh avenue for investigation to determine the most suitable proportions of spring pressure and inertia of the pressure finger in order to obtain the best all-round performance.

THE RESONANCE METHOD OF WAVE-FORM ANALYSIS.*

By C. F. J. MORGAN, M.Sc., Graduate.

(*Paper first received 2nd September*, 1930, *and in final form 17th August*, 1931.)

SUMMARY.

The paper describes briefly the principles of the resonance method of wave-form analysis. A short account is included of the other methods of analysis that are available, and a historical *résumé* of the resonance method is given. The desirability of basing the analysis on a measurement of the voltage across the inductance coil in the resonance circuit is demonstrated from theoretical and practical considerations. The most suitable form of analyser is described and the advantages of the thermionic voltmeter for this purpose are indicated. A selection of the results obtained are included to illustrate the applications of the method.

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List of Symbols.
(1) Introduction.
(2) Theory of the resonance method.
(3) Other methods of wave-form analysis.
(4) Historical *résumé*.
(5) Description of experimental work.
(6) Practical form of resonance analyser.
(7) Selection of results obtained.
(8) Conclusions.

Appendices.
I. Design of a suitable inductance coil.
II. Specimen observation sheet.
III. Bibliography.

LIST OF SYMBOLS.

C = capacitance.
E = R.M.S. value of e.m.f. under analysis.
E_C = e.m.f. across condenser in resonance circuit.
E_L = e.m.f. across inductance in resonance circuit.
E_r = e.m.f. across resistance r in resonance circuit.
E_m = mth-order harmonic component of E (component in resonance).
E_n = nth-order harmonic component of E (any component not in resonance).
f = supply frequency.
I = circuit current.
I_m = mth-order harmonic component of I.
L = inductance.
m = order of in-resonance harmonic.
R = total ohmic resistance of circuit.
$\omega = 2\pi f$.

(1) INTRODUCTION.

It was first pointed out by Fourier that any periodic function may be represented as the sum of a number of sine components of different frequencies, these components being called "harmonics." It is well known that the best way of investigating any problem of distorted waves is to consider the separate harmonics present. In electrical engineering practice the ideal wave-form of voltage or current is usually a sine wave, and distortion of this ideal form due to harmonics frequently produces undesirable results. Thus it becomes important to have some method of determining the various harmonic components present in any distorted wave-form. The various methods which have been suggested may be classified as (*a*) *indirect methods*, in which a graphical representation of the wave-form has first to be obtained, and the curve is then analysed into its harmonic components; or (*b*) *direct methods*, in which the harmonics are determined directly from the readings of one or more instruments.

The method which has been most widely used consists of an analysis of an oscillogram of the wave-form. This process is inconvenient and lacking in accuracy. The resonance method described in this paper will perhaps meet the existing need for a convenient "direct" method of analysis.

(2) THEORY OF THE RESONANCE METHOD.

In the resonance method the e.m.f. which is to be analysed is applied to a circuit (Fig. 1) containing

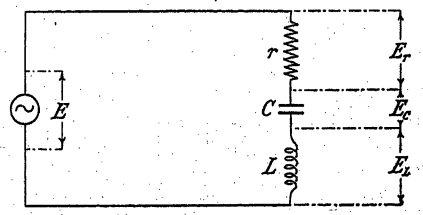


FIG. 1.

inductance, capacitance, and resistance, in series. Either the capacitance or the inductance is varied until the natural frequency of the circuit coincides with the frequency of the particular harmonic to be measured. This component will be referred to as the "in-resonance" component, the others being "out-of-resonance" components. The magnitude of the in-resonance component may be calculated from the value of the voltage across the capacitance, the resistance, or the inductance. For, to a first approximation, it may be assumed that at resonance the circuit current is produced solely by the in-resonance harmonic.

Then
$$I = E_m/R \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$E_C = \frac{I}{Cm\omega} = \frac{E_m}{R} \cdot \frac{1}{Cm\omega} = E_m \frac{Lm\omega}{R} \quad . \quad . \quad (2)$$

* The author was awarded a Student's Premium for a paper on this subject read before the London Students' Section on the 15th March, 1929. The paper has been amplified for publication in the *Journal*.

since, at resonance,

$$Lm\omega = 1/(Cm\omega)$$

also $$E_r = Ir = E_m\frac{r}{R} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and $$E_L = ILm\omega = E_m\frac{Lm\omega}{R} \quad . \quad . \quad . \quad (4)$$

Hence the magnitude of the component E_m is given by

$$E_m = E_C \,.\, RCm\omega = E_C \cdot \frac{R}{Lm\omega}, \text{ from (2)}$$

From (3), $$E_m = E_r\frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

or, from (4), $$E_m = E_L\frac{R}{Lm\omega} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The assumption that the out-of-resonance components produce no current is, of course, untrue, so that the expressions deduced for E_m are inaccurate. The extent of the inaccuracy may be readily deduced by considering the currents produced by the out-of-resonance components. This has been done by Prof. R. Beattie,* from whose work the following deductions are made.

It is seen that three resonance methods of analysis are available according as the calculation is based on a measurement of the voltage across the capacitance, the resistance, or the inductance; these three will be referred to as methods A, B, and C respectively.

In the case of method C, the expression for E_m given in equation (6) assumes that the ohmic resistance of the circuit is small compared with the reactance of the coil. It therefore becomes important to design a coil of large inductance for a given resistance; the ratio $L\omega/R$ should be not less than 5.

The mathematical examination of the resonance circuit proves that method B will probably be more accurate than method A, and that method C will probably be more accurate than either method A or method B. This proposition cannot be rigidly established for all wave-forms, but it is true for those likely to be met with in electrical engineering problems. This conclusion is supported by the examination of a large number of widely differing wave-forms; as an illustration, Tables 1 and 2 give the percentage errors of the three resonance methods A, B, and C, for two wave-forms. In the calculations for both tables the value of $L\omega/R$ is assumed to be 5.

A simply-calculated correction factor may be applied to the results obtained by any one of the three methods. This has been done for method A in the above examples, and it clearly gives a close approximation to the true value.

The correction factor is given by

$$\sqrt{[1 - (1/S^2)]}$$

where $$S = \frac{E'_m\, Lm\omega/R}{\sqrt{\left\{\sum\left[E'_n\frac{m^2}{m^2 - n^2}\right]^2\right\}}}$$

the values of E'_m and E'_n being taken from the inaccurate analysis first obtained.

* See Bibliography, (31).

This correction factor may be applied with little difficulty if only one or two of the out-of-resonance components have to be corrected for. It is, however, very inconvenient to apply the correction factor if there are a large number of components.

TABLE 1.

Component	True value	Value given by method A	Percentage error		
			Method A (corrected)	Method B	Method C
Fundamental ..	100	—	—	—	—
3rd harmonic ..	15	11·75	$0·0_0$	$1·4_8$	$0·4_5$
5th harmonic ..	10	8·80	$0·0_0$	$0·5_6$	$0·1_7$
7th harmonic ..	5	$16·6_7$	$0·6_0$	$0·8_6$	$0·3_2$
9th harmonic ..	3	$26·4_0$	$0·0_0$	$0·9_5$	$0·3_3$
11th harmonic ..	2	37·0	$0·6_0$	$0·8_0$	$0·2_5$

Experience shows that if method C is adopted the only case where serious inaccuracy is likely to arise is that of a small 3rd harmonic in the presence of a large 5th. The correction factor need never be applied, except in cases of this sort. The only out-of-resonance components to be considered are the 5th and the fundamental. For example, if the correction factor be applied to the value for the 3rd harmonic in the second of the above wave-forms, the corrected value is accurate to within 0·1 per cent.

TABLE 2.

Component	True value	Value given by method A	Percentage error		
			Method A (corrected)	Method B	Method C
Fundamental ..	100	—	—	—	—
3rd harmonic ..	4	133·5	0·45	19·0	5·8
5th harmonic ..	10	7·7	0·1	0·4	0·1
7th harmonic ..	5	16·3	0·0	0·7	0·2

Instead of the mathematical argument by which Prof. Beattie established the great probability of method C being more accurate than methods A and B, the following physical explanation is advanced.

It is necessary to assume that the harmonic components of low order will in general be of greater magnitude than those of high order. Almost invariably this assumption is justified, for the fundamental far exceeds any other component. Considering the effect of the fundamental when the circuit is tuned to resonance with the mth-order harmonic, we have

Voltage across the condenser due to fundamental

$$= I_1(1/C\omega)$$
$$= I_1(L\omega m^2)$$

Voltage across the coil due to fundamental

$$= I_1 L\omega$$

Hence the fundamental produces a much smaller voltage across the coil than across the condenser.

The in-resonance component, however, produces the same e.m.f. across both the coil and the condenser: it follows that this component forms a much larger proportion of the coil voltage than it does of the condenser voltage.

For harmonics of higher order than the in-resonance component, the opposite is true, i.e. the out-of-resonance component is greater in the coil voltage than in the condenser voltage. Our initial assumption entitles us to suppose, however, that this effect is far outweighed by that of the low-order harmonics. Hence it is much more accurate to assume the coil voltage, and not the condenser voltage, to be due entirely to the harmonic which is being measured.

(3) Other Methods of Wave-Form Analysis.

Before the resonance method is discussed in detail, the other methods of wave-form analysis will be briefly considered.

(*a*) *Indirect methods.*

The graphical representation of a wave-form was obtained originally by using the "contact principle" which was introduced in 1881 by Joubert and improved by Blondell and Hospitallier. Their methods all involve lengthy and laborious point-to-point determinations. Variations of the contact principle have been described by Duncan,* Ryan,† Goldschmidt,‡ and Laws.§

In Duncan's and Ryan's methods the current under analysis is passed through one coil of a dynamometer. The other coil carries a current only at that instant of each half-cycle for which the reading is required. In Goldschmidt's method the current is passed through the primary of a transformer, and the magnetic circuit of this transformer is completed at a particular instant each half-cycle. Observation of the secondary current affords a measure of the current magnitude at this point of the wave. Laws's method is the same in principle as Goldschmidt's. These methods require the measurement of the instantaneous value of a current. For accuracy, the duration of the impulse on the measuring instrument must be made small, and, as the sensitivity of the instrument is much reduced in consequence, considerable error may be introduced.

The best way of obtaining a graphical representation of the wave-form is to use an oscillograph. Of the various types of oscillographs which are available, viz. the moving-coil, electrostatic, and cathode-ray forms, the one most commonly used in practice is the Duddell moving-coil instrument. One of its limitations is that it gives results of doubtful accuracy when used to determine harmonics of orders higher than 11. The analysis of an oscillogram can be carried out by (*a*) A Coradi or other type of mechanical analyser, or (*b*) graphical construction, or (*c*) calculation from the measurement of selected ordinates. There is a considerable amount of literature dealing with these methods.‖

Even in the shortened forms available, indirect methods are cumbersome, and further, especially when high-order harmonics have to be determined, they lead to considerable errors.

(*b*) *Direct methods.*

The resonance method belongs to this class, and among others which have been suggested there are:—(i) rectifying, (ii) potentiometer, (iii) dynamometer, and (iv) heterodyne methods.

(i) *Rectifying methods.**—The principle of these is identical with that of the Fischer-Hinnen† method of analysis by the measurement of selected ordinates of an oscillogram. The rectifying methods perform the summation mechanically. For the determination of a particular harmonic the rectifying method is very laborious.

(ii) *Potentiometer method.*‡—In this method an a.c. potentiometer is adjusted to the null position, using the e.m.f. under analysis. The phase of one of the currents is then shifted by 120°, so that current is produced by all the harmonics except the 3rd, 9th, 15th, etc. The current is measured by means of a galvanometer. The phase shift is then altered to 72°, when the only harmonics not producing current are those of order $5n$ (where n is a positive odd integer). In this way a series of galvanometer readings is taken for various phase settings. Corresponding to each observation an equation may be established having the amplitudes of the harmonics as the unknown quantities. By making a sufficient number of observations these equations may be solved and the harmonic components determined.

Since the potentiometer is not being used as in a null method, its accuracy is greatly reduced. Further, for a complete analysis when many harmonics have to be determined, the number of simultaneous equations becomes excessively large.

(iii) *Dynamometer method.*—Essentially this method consists in applying the e.m.f. to be analysed to one coil of a dynamometer while the other carries a sinusoidal current of the same frequency as the harmonic being measured. The deflection of the dynamometer is then proportional to the product of the sinusoidal analysing current and the magnitude of the harmonic which is being measured. In order to develop a practical analyser on these lines it is necessary to consider the following requirements. (*a*) The analysing current must be truly sinusoidal. (*b*) It must be obtainable over a wide range of frequencies in order to measure the high-order harmonics. (*c*) It must be exactly in phase with the harmonic to be measured.

The first successful analyser of this type was described in a paper read before the Institution in 1925.§ This paper discusses very fully the theory and application of the dynamometer method. The difficulty of obtaining a suitable sinusoidal analysing current was overcome by using the properties of an oscillatory circuit. It was found possible to measure all the harmonics up to the 23rd with an accuracy of 0·1 per cent of the fundamental. This is much better than the accuracy obtainable by the indirect methods. Unfortunately the apparatus required for the analyser is of a special and costly nature.

* See Bibliography, (2). † *Ibid.*, (3). ‡ *Ibid.*, (4). § *Ibid.*, (5).
‖ See, for example, Bibliography, (8) to (12).

* See Bibliography, (13), (14), and (15).
† *Ibid.*, (6). ‡ *Ibid.*, (16). § *Ibid.*, (20).

A paper by R. T. Coe* describes a further development of this analyser in which the sinusoidal analysing current is obtained by using a special synchronously-driven contact disc in conjunction with a valve circuit. This analyser is claimed to measure harmonics of a few per cent of the fundamental with an accuracy of 0·05 per cent, and very feeble harmonics to within 0·01 per cent of the fundamentals. It is arranged for a frequency range up to the 41st harmonic of a 50-cycle supply. The apparatus, though less complicated than that of the original analyser, is still of a special nature.

(iv) *Heterodyne method.*†—This method has only recently been introduced. C. Suits‡ has tested the sensitivity and accuracy obtainable by using the method to analyse known wave-forms. It is claimed to be accurate to within 1 per cent for harmonics of magnitude 10 per cent of the fundamental, and to within 3 per cent for harmonics of magnitude 1 per cent of the fundamental.

(4) Historical Résumé.

The possibility of analysing a wave-form by the resonance method was first suggested by H. I. Pupin in 1894.§ Pupin employed an electrometer to measure the voltage across the condenser (see Fig. 1), and neglected the effect of all except the in-resonance component.

Other investigators measured circuit current instead of condenser voltage, on account of the greater convenience of using an ammeter instead of an electrostatic voltmeter. The first to make use of this modification seems to have been T. Mather,|| who discovered it almost by accident in 1901.

Among others to attempt an analysis from a measurement of circuit current were H. Armagnat¶ and E. Orlich,** both of whom used an oscillograph to record the current. A fixed measured capacitance was included, the circuit being tuned by a variable inductance coil of the Ayrton-Perry type.†† As the natural frequency of the circuit approached that of a particular harmonic, that harmonic was depicted on the screen of the oscillograph as an approximately sinusoidal wave. The amplitude of this wave was measured when it reached its maximum, and as the terminal-e.m.f. wave was also depicted on the screen (by means of a second element on the oscillograph) the comparative magnitude of the harmonic could be obtained. Although this arrangement affords an exceedingly picturesque illustration of the method, the results obtained from it are inaccurate, especially for small harmonics.

An automatic analyser of this type which has been invented in America by R. L. Wegel and C. H. Moore‡‡ is described as an "electrical frequency analyser." The current in the tuned circuit is applied through a high-ratio transformer to a valve amplifier, and is registered on a recording meter. The tuning capacitance is automatically varied in small steps by a pneumatic device. The record is taken on a specially-scaled photographic plate which is moved across the recording meter by pneumatic power: thus the curve obtained shows circuit current plotted against natural frequency of the circuit. The peak ordinates on this curve are taken as a measure of the harmonics to which they correspond. The designers of this analyser state that when taking a record it is only necessary to start the amplifier, connect to a 110-volt supply, attach the leads to the source to be analysed, and press a button. The completed record is delivered after about 5 minutes, when the mechanism automatically re-sets itself. This process represents a maximum of rapidity, but its accuracy is poor. It appears that no attempt has been made to design a suitable coil having a large amplification factor, and as all the harmonics are recorded on the same scale small components cannot be accurately determined.

An interesting application of the resonance method is described in a paper read before the Institution by B. A. G. Churcher and A. J. King* on "The Analysis and Measurement of the Noise Emitted by Machinery." The energy of sound being very small, exceedingly sensitive apparatus must be employed for its analysis. The problem is complicated by the fact that the components of a noise are not simple harmonics of the fundamental, but may have quite independent frequencies. Churcher and King's method is to amplify the small e.m.f. generated in a detecting microphone before applying it to the analyser. In order to obtain good selectivity without using a large inductance coil, a double-circuit analyser is used. The secondary current is measured by a vacuum thermo-junction and a portable reflecting galvanometer. Very satisfactory results have been obtained with this apparatus.

The first searching examination of the theory of the resonance method was published in 1912 by Prof. Beattie,† whose work forms the starting-point of the present investigations. His theoretical deductions are set out in the following section. Since the publication of his original paper several other investigations‡ have been made into the same subject.

(5) Description of Experimental Work.

The first object of the experimental investigation was to verify the theoretical conclusions set out in the previous section. For this purpose the same wave-form (frequency, 100) was analysed by each of the three resonance methods. This wave-form was first analysed from an oscillogram, and the following components were observed:—

Fundamental	100
3rd harmonic	14·2
5th harmonic	9·0
7th harmonic	3·2

Feeble harmonics of higher orders were also present, but for the moment they need not be considered.

The voltages across the condenser and across the coil were measured by an electrostatic voltmeter over a range of values of the capacitance. For method B the ohmic drop was calculated from the circuit current, which was measured by a low-range dynamometer. Although the apparatus used for these initial experiments lacked refinement, the results definitely showed that method C gave the greatest accuracy. The apparatus was later

* See Bibliography, (21). † *Ibid.*, (22), (23), and (24).
‡ *Ibid.*, (23). § *Ibid.*, (25). || *Ibid.*, (26). ¶ *Ibid.*, (27).
** *Ibid.*, (28). †† *Ibid.*, (40). ‡‡ *Ibid.*, (29).

* See Bibliography, (30). † *Ibid.*, (31). ‡ *Ibid.*, (32), (33), and (34).

modified in order to ensure greater convenience and increased accuracy.

Two fundamental modifications were introduced. In the first place, the capacitance for tuning the circuit was arranged to be continuously variable so as to enable the peak value of the voltage being measured to be observed directly. A great saving of time was effected by this modification, which increased the accuracy of the equipment because it enabled the true peak value to be obtained.

The second change consisted in the substitution of a thermionic voltmeter* for the electrostatic type previously employed. It is necessary to employ a high-impedance voltmeter, and although both the electrostatic and the thermionic types fulfil this condition the latter is much more sensitive than the portable electrostatic instrument, which also suffers from the disadvantage that it requires a long time-interval before giving a steady reading. The thermionic voltmeter, on the other hand, responds rapidly to any voltage change, and enables a reading to be taken within a few seconds: it is also suitable for the measurement of quite small voltages and has an open scale. The modified apparatus used for the further experiments is represented diagrammatically in Fig. 2.

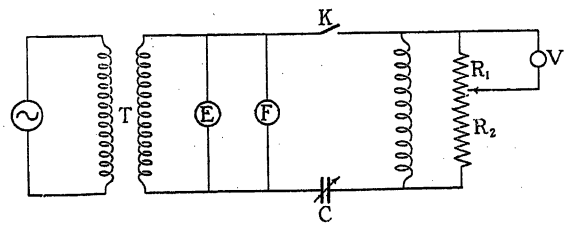


FIG. 2.

C was a continuously-variable mica condenser of $0{\cdot}01$ μF maximum capacitance. It was used for the final adjustment only. Larger variations were obtained by the use of a bank of condensers whose capacitance could be varied in steps of $0{\cdot}01$ μF from $0{\cdot}01$ to $0{\cdot}60$ μF simply by rotating two contact switches. For capacitances greater than $0{\cdot}6$ μF condensers were connected in parallel, but this necessity did not frequently arise. The Dubilier condenser units employed could be safely operated at an a.c. voltage of 300 volts, the highest value required. Mica condensers were found to give more reliable results than paper condensers, and they also have the advantage of being of small bulk. The bank used was very compact, its dimensions being $25 \times 20 \times 10$ cm.

The choice of a suitable inductance coil is a matter of great importance. As a high amplification factor is desirable, the coil must have a large time-constant and this is ensured (see Appendix I) by adopting the proportions given by C. J. Maxwell.†

The thermionic voltmeter V employed the curvature of the anode-current/grid-voltage characteristic, the circuit being arranged as in Fig. 3. The input voltage was measured in terms of the plate current as recorded by the unipivot milliammeter G (made by the Cambridge Scientific Instrument Co.). A Marconi D.E.5a power valve was found to be convenient for these tests. It was operated with a filament voltage of $5{\cdot}6$ volts, an anode voltage of 48 volts, and a negative grid-bias of $17{\cdot}5$ volts. These conditions were chosen so that the working range of the voltmeter occurred at a section of considerable curvature on the anode-current/grid-voltage characteristic, thus ensuring high sensitivity. To secure a high impedance, the grid must be negatively charged to such an extent that even at the peak value of the maximum applied voltage it still remains negative, no current being then taken from the input circuit.

Accuracy is increased if the initial deflection of G—without any applied voltage—is of appreciable magnitude. With the conditions detailed above an initial deflection of 41 units was obtained, the full-scale deflection being 150 units. The instrument zero (i.e. a 41-unit deflection) was maintained constant by adjusting the filament current. The voltmeter was calibrated on direct current against a dynamometer-type voltmeter for which a National Physical Laboratory calibration was available.

The valve voltmeter in the form used had a range of

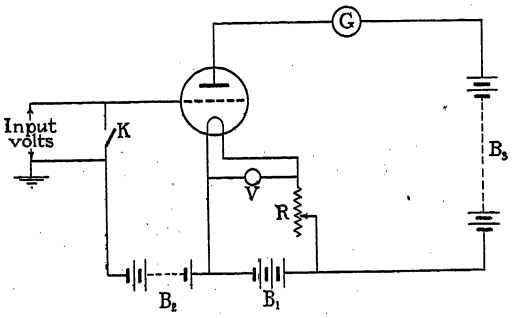


FIG. 3.

0 to 4 volts. When measuring up to 300 volts a potentiometer was used to tap off a known proportion of the required e.m.f. The potentiometer consisted of a divided megohm in series with a 100 000-ohm resistance variable in steps of 10 000 ohms.

The procedure when making an analysis was to adjust the capacitance approximately to the value required for resonance with a particular harmonic, vary the reading of the potentiometer R_1R_2 until nearly full-scale deflection of G was obtained, and finally adjust the condenser until the milliammeter deflection passed through its maximum value. The form of observation sheet found most suitable is given in Appendix II. This procedure enabled a wave-form containing some twelve harmonics to be analysed in about half an hour.

(6) PRACTICAL FORM OF RESONANCE ANALYSER.

The apparatus described in the previous section, whilst giving reliable results in the laboratory, does not constitute the most convenient form for use in engineering practice. A description will now be given of apparatus suitable for a practical analyser.

(*a*) *Voltmeter.*—This will be required for measuring the terminal e.m.f.

(*b*) *Frequency meter.*—For recording the frequency of the e.m.f. under analysis a reed-type frequency-meter would, generally speaking, be sufficiently accurate.

* See Bibliography, (36) and (37). † *Ibid.*, (38).

In exceptional cases the frequency could be calculated by observing the capacitance included to give resonance with each harmonic.

(*c*) *Potentiometer.*—This is connected across the inductance coil and must have a large impedance. A resistance of 1 megohm would be suitable. Tapping points should be arranged so that convenient fractions of the coil voltage may be measured.

(*d*) *Thermionic voltmeter.*—The instrument manufactured by the Cambridge Instrument Co. under the Moullin patent is accurate, convenient, and, on account of its size, easily portable.

(*e*) *Inductance coil.*—It has been pointed out that the coil used must have a maximum inductance for a given resistance. The design of such a coil is considered in detail in Appendix I, where it is shown that a suitable coil can be developed which will weigh not more than 35 lb. The inductance of the coil used must be accurately measured by a bridge method.

(*f*) *Condensers.*—The range of capacitance required depends on the frequencies of the e.m.f.'s to be analysed. It is not necessary to measure the fundamental of the wave-form, as this may be calculated from the R.M.S. value and the values of the harmonics. The greatest capacitance required, therefore, is that needed to tune the circuit to resonance with the third harmonic. If an inductance of 0·5 henry is used the capacitance required for a 50-cycle wave-form is only 2·25 μF, and even at 20 cycles per sec. it is no more than 14 μF.

As already pointed out, good-quality condensers are desirable. Although the magnitude of the capacitance is not needed for the analysis calculations, it is desirable to know it fairly accurately as the rapidity of tuning of the circuit is thereby much increased. In choosing the condenser arrangement two factors have to be considered, viz. rapidity of manipulation, and cheapness of construction.

It is probably best to have a bank of condensers variable from 0 to 0·1 μF in steps of 0·01 μF, and another bank variable from 0 to 1·0 μF in steps of 0·1 μF. It should be possible to vary the capacitances by rotating a contact arm: larger condensers variable in steps of 1·0 μF might be of the plug-in or tumbler-switch type. Finally, a continuously-variable condenser of 0·01 μF maximum capacitance is required. This condenser must be capable of fine adjustment. All the apparatus is of standard laboratory type, and the whole equipment might be assembled in a semi-portable form convenient for use in laboratory or test department.

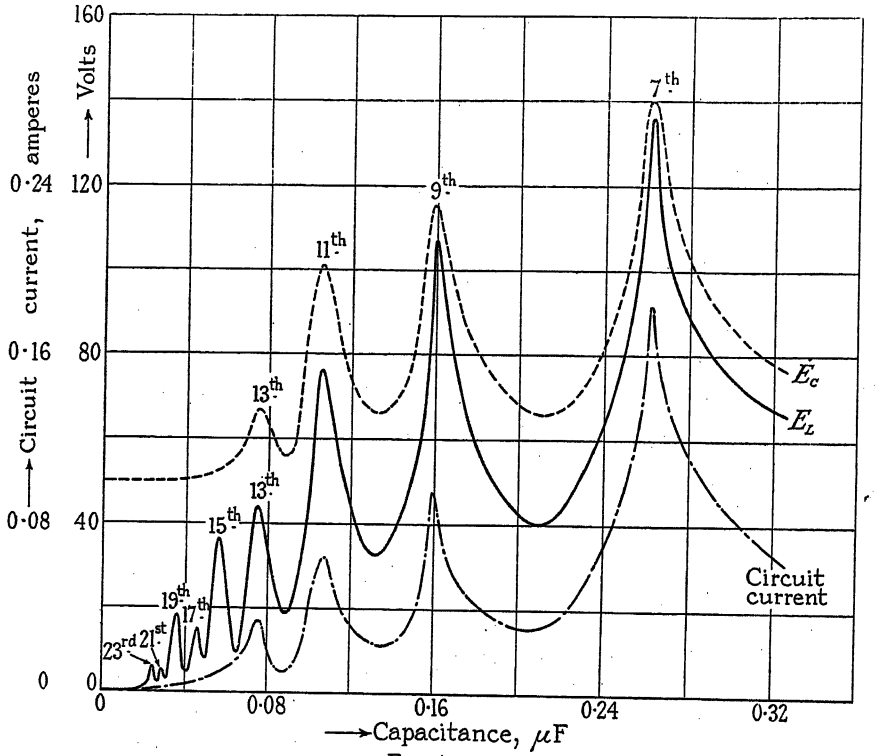


FIG. 4.

No particular manipulative skill is required in the use of the analyser, and the only observations necessary for the determination of any harmonic are (*a*) maximum value of thermionic-voltmeter reading, (*b*) terminal voltage, and (*c*) potentiometer ratio.

(7) SELECTION OF RESULTS OBTAINED.

The analyser was applied to the analysis of the wave-form of a Pyke-Harris alternator. The thermionic voltmeter was used for methods A and C, but it is somewhat difficult to adapt it to method B since a large resistance would have to be included in the resonance circuit. As a basis of comparison of the three methods, the circuit current was measured by a low-range dynamometer instrument. The curves representing E_c, E_r, and E_L, are plotted in Fig. 4, the calculated analysis being presented in Table 3.

All the odd harmonics up to the 23rd were measured by method C. In methods A and B the highest-order harmonic observed was the 13th. The reason for the greater range of method C as compared with method A is seen from the curves, which show that the condenser voltage is at least equal to the applied e.m.f., so that a small harmonic produces relatively little voltage rise across the condenser. The coil voltage, on the other hand, depends almost entirely upon the in-resonance harmonic, so that in this case the voltage rise is much more noticeable. For example, the curves show that for the 13th harmonic the voltage rise in method A is from 56 to 67 volts, i.e. approximately 20 per cent, whereas in method C it is from 9 to 46 volts, i.e. more than 400 per cent. Although method B compares unfavourably with method C, it should be understood that the apparatus used for the current measurement lacked the refinement of the thermionic voltmeter. Nevertheless, better results cannot be obtained by method B using commercial instruments; and the results quoted do, in fact, establish that method C is the most suitable for development.

TABLE 3.

Comparison of Methods A, B, and C.

Component	Method A	Method A (corrected)	Method B	Method C
Fundamental	100	100	100	100
3rd harmonic	$15 \cdot 2_0$	$14 \cdot 3_0$	14·9	$14 \cdot 3_0$
5th harmonic	$9 \cdot 5_0$	$9 \cdot 0_3$	$9 \cdot 4_5$	$9 \cdot 0_4$
7th harmonic	$3 \cdot 9_1$	$3 \cdot 3_2$	$3 \cdot 9_5$	$3 \cdot 1_5$
9th harmonic	$2 \cdot 4_4$	$1 \cdot 8_4$	$2 \cdot 0_3$	$1 \cdot 78_7$
11th harmonic	$1 \cdot 8_0$	$1 \cdot 2_1$	$1 \cdot 3_8$	$1 \cdot 04_0$
13th harmonic	$1 \cdot 2_1$	$0 \cdot 65_2$	$0 \cdot 7_5$	$0 \cdot 52_6$
15th harmonic	—	—	—	$0 \cdot 36_2$
17th harmonic	—	—	—	$0 \cdot 12_3$
19th harmonic	—	—	—	$0 \cdot 14_2$
21st harmonic	—	—	—	$0 \cdot 030_6$
23rd harmonic	—	—	—	$0 \cdot 032_1$

The analysis of the wave-form of the Pyke-Harris alternator was repeated after a period of some months. The results obtained were found to be in close agreement with those of the original analysis, the greatest difference between the two sets of values being not more than 2 per cent. The normal frequency of the alternator was 100, but tests were performed at half speed and quarter speed, practically identical wave-forms being obtained.

A useful application of the resonance analyser is to the measurement of the harmonic components of a tooth ripple in the wave-form. These components are of the order $(2n \pm 1)$, where n represents the number of armature slots per pole. It was found that such harmonics are almost invariably present, though the oscillograph often fails to discover them. A wave-form having a very pronounced tooth ripple was found to contain a 23rd harmonic of 1·01 per cent of the fundamental, and a 25th harmonic of $0 \cdot 63_7$ per cent of the fundamental. In another case the analysis of the wave-form of a rotary-convertor alternating current showed the tooth-ripple components to be the 29th and 31st harmonics, which were equal to $0 \cdot 006_4$ and $0 \cdot 004_3$ per cent of the fundamental respectively.

From the results obtained three examples have been selected and their analyses are shown in Table 4. Particulars will now be given of these examples:—

Example (a). Voltage Wave-Form of 400-volt 25-cycle Single-Phase Rotary Convertor, 4 poles, 750 r.p.m.

The only harmonics detected in the oscillogram of this wave-form were the 3rd and the 5th, of 2·5 and 1·4 per cent of the fundamental respectively. The analysis by the resonance method, however, revealed 15 harmonics, and a harmonic of the 119th order was measured. For measuring such high orders it is necessary to know very exactly the value of the capacitance included at resonance. This is naturally very small, and a minute error in its magnitude would result in the wrong order being assigned to the particular component under investigation.

TABLE 4.

Component	Example (a)	Example (b)	Example (c)
Fundamental ..	100	100	100
3rd harmonic ..	$2 \cdot 33_1$	—	$1 \cdot 37_2$
5th harmonic ..	$0 \cdot 96_7$	$2 \cdot 15_0$	$0 \cdot 47_3$
7th harmonic ..	$0 \cdot 079_6$	$0 \cdot 97_1$	$0 \cdot 19_5$
9th harmonic ..	$0 \cdot 126_0$	—	$0 \cdot 075_2$
11th harmonic ..	$0 \cdot 078_3$	0·204	$0 \cdot 068_3$
13th harmonic ..	$0 \cdot 032_0$	$0 \cdot 131_2$	$0 \cdot 028_8$
15th harmonic ..	$0 \cdot 017_9$	—	—
17th harmonic ..	$< 0 \cdot 00_4$	1·205	$0 \cdot 022_2$
19th harmonic ..	$< 0 \cdot 00_4$	0·567	$0 \cdot 012_7$
21st harmonic ..	$0 \cdot 027_8$	—	—
23rd harmonic ..	$0 \cdot 032_4$	—	—
25th harmonic ..	$0 \cdot 030_0$	—	—
37th harmonic ..	—	$0 \cdot 020_8$	—
41st harmonic ..	$0 \cdot 010_2$	—	—
47th harmonic ..	$0 \cdot 016_6$	—	—
71st harmonic ..	$0 \cdot 012_6$	—	—
95th harmonic ..	$0 \cdot 008_1$	—	—
119th harmonic ..	$0 \cdot 007_4$	—	—

A test was performed with this convertor running at half speed, so that it generated a 12·5-cycle wave-form. At this low frequency two additional components were detected, the 143rd and the 199th, of $0 \cdot 0079_4$ and $0 \cdot 0025_1$ per cent of the fundamental respectively. These figures show that the equipment may be applied to the analysis of low-frequency wave-forms and that it will measure components of exceedingly small magnitude; for the small 199th harmonic referred to would give an e.m.f. of 1·7 volts across a 0·5-henry inductance coil. This voltage could be measured with ease on a thermionic voltmeter.

Example (b). Voltage Wave-Form of 100-volt 50-cycle 3-phase Star-Connected Alternator, 4 poles, 1 500 r.p.m.

The absence of harmonics whose order is a multiple of 3 is in accordance with well-known theory. The

prominent 17th and 19th harmonics are the tooth-ripple components, there being 9 armature slots per pole. As these two harmonics are of appreciable magnitude and high frequency (850 and 950 cycles per sec. respectively) they might prove to be a serious source of interference with neighbouring telephone circuits.

The alternator from which this wave-form was obtained is one of two similar machines used in laboratory back-to-back tests. The wave-form of the second machine was analysed and found to be within 1 per cent of that of the first for each harmonic. The machines are of the rotating-armature type, and, as is usual with this design, have no strong harmonics. The analysis of the wave-forms was repeated after an interval of several months, the results obtained agreeing almost exactly.

Example (*c*). *Wave-Form of Phase Voltage of Manchester Corporation 50-cycle 3-phase Supply.*

The phase voltage of this supply is approximately 237 volts; it was stepped down by a suitable transformer before being analysed. Since the generating plant is of the most modern type only small harmonics were to be expected. The analysis confirmed this prediction, for of the eight harmonics measured the largest was the third (1·4 per cent of the fundamental). It was thought that the wave-form of the supply might be subject to variations during the day as the load varied. As a further test, therefore, the third harmonic was measured at intervals of 1 hour over a period of 26 hours. A very considerable variation in the magnitude of the harmonic was observed: it had a minimum value of $1 \cdot 10_3$ per cent of the fundamental at 8·30 a.m., and a maximum of $1 \cdot 64_6$ per cent of the fundamental at 5.30 p.m. This test revealed another interesting feature: it was found that the supply frequency varied by about 1 per cent during the day. This was discovered by observing the capacitance required to produce resonance with the third harmonic, i.e. by making use of the principle of the resonance frequency-meter.

The wave-forms analysed during the course of this investigation varied greatly in respect of the number and magnitude of the harmonic components present. Wave-forms of frequencies ranging from 12·5 to 500 were analysed. No difficulty was experienced under all these different conditions in obtaining an exhaustive analysis.

(8) Conclusions.

A convenient direct method of wave-form analysis would possess many advantages over the existing indirect methods. The resonance method should satisfy all the requirements for a suitable direct method. It has been criticised in the past on the grounds that:—

(*a*) *Readings obtained for one harmonic are influenced by other harmonics.*—It was thought that the resultant error would be excessive unless a choking coil having a very low damping factor was employed. Such a coil would necessarily have either an iron core or an excessive amount of copper; in either case it would be very heavy. It may be shown, however (see Appendix I), that accuracy is obtainable by using a coil of only moderate weight. The error is greatly reduced by measuring the voltage across the inductance coil instead of that across the condenser.

(*b*) *Difficulty arises in obtaining accurate readings for the peak values of the current, due to small variations from exact resonance frequency.*—With the arrangement embodying the thermionic voltmeter and continuously variable tuning, no difficulty was experienced in obtaining the peak values. The frequency of the e.m.f. under analysis may vary slightly, but the tuning is quite sharp enough to enable one to detect the true maximum point.

(*c*) *The effect of eddy-current losses in the iron and copper and of hysteresis losses in the iron and dielectric cause a change in effective resistance with frequency.*—This assumes the use of an iron-core choking coil, but as an air-core coil may be employed the actual error can be made quite small. Measurements over a range of frequencies from 25 to 2 000 failed to disclose any change in the effective resistance of the coil.

To summarize briefly the position of the resonance method, the investigation has demonstrated that (i) the most accurate results are obtained by measuring the voltage across the inductance coil; (ii) the method affords an accurate determination of harmonics of small magnitude, and is readily applicable to the measurement of high-order harmonics; (iii) it enables e.m.f. waves of frequencies up to at least 500 to be simply and rapidly analysed; (iv) it only demands the use of ordinary laboratory instruments; and (v) the analysis is in all cases accurate to within 1 per cent.

The investigation recorded in this paper was carried out in the John Hopkinson Laboratories of Manchester University under the direction of Prof. R. Beattie, to whom the author is indebted for much valuable advice and also for permission to publish the results.

APPENDIX I.

Design of a Suitable Inductance Coil.

The inductance coil should be designed to have a large time-constant. Provided the value of $L\omega/R$ exceeds 5, accurate results may in general be obtained, although a larger value is desirable. If a coil is to have maximum inductance for a given resistance its proportions must be those suggested by C. J. Maxwell.* The coil is then of the form represented in Fig. 5, where

$$D_0/D_1 = 47/27$$
$$D = 3 \cdot 7a$$

A coil of these proportions can be designed so as to have any required inductance. As an example, the design of a 0·5-henry inductance coil will be considered; the method followed is that given by Sir Ambrose Fleming.†

From the formula of Mascart and Jouberts

$$L = 3 \cdot 1\pi DN^2 \quad . \quad . \quad . \quad . \quad . \quad (i)$$

where the inductance L is measured in absolute units and N is the total number of turns.

* See Bibliography, (38). † *Ibid.*, (39).

Let l = total length of wire,
d = diameter of the bare wire,
and d' = diameter of the covered wire.

Then $$l = \pi DN \quad . \quad . \quad . \quad . \quad . \quad . \quad (ii)$$

and $$a = \sqrt{(N)}d' \quad . \quad . \quad . \quad . \quad . \quad . \quad (iii)$$

But $$D = 3{\cdot}7a$$

$$\therefore \quad D = 3{\cdot}7\sqrt{(N)}d'$$

Substituting this value for D in equation (i),

$$L = 3{\cdot}1\pi\left[3{\cdot}7\sqrt{(N)}d'\right]N^2$$
$$= 36d'N^{5/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (iv)$$

It is now necessary to decide upon the gauge of wire to be used. That chosen must be capable of carrying

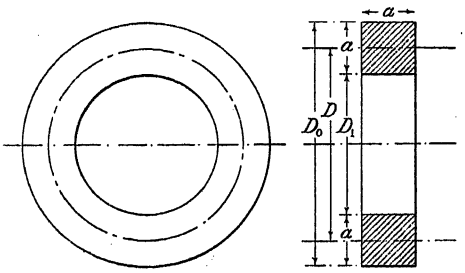


FIG. 5.

a current of, say, 1 ampere, so that the diameter should at least exceed 0·030 in. Let us first consider 0·048-in. diameter double-cotton-covered wire (No. 18 S.W.G.).

$$\text{Diameter} = 1{\cdot}219 \text{ mm}$$
$$d' = 1{\cdot}473 \text{ mm}$$

The number of turns may be calculated from equation (iv).

For $$0{\cdot}5 \times 10^9 = 36 \times 0{\cdot}1473 \times N^{5/2}$$

whence $$N^{5/2} = 10^{10}/106$$

Therefore $$N = 10^4/106^{2/5}$$
$$= 1\,550 \text{ turns}$$

Now $$D = 3{\cdot}7\sqrt{(N)}d' = 21{\cdot}5 \text{ cm}$$

also $$l = \pi DN = 105\,000 \text{ cm}^*$$

* The weight of 1 050 metres of 0·048 in. copper wire is 24 lb.

The resistance is now calculated, and found to be given by

$$R = 15{\cdot}25 \text{ ohms}$$

Hence the amplification factor of the coil at 50 cycles per sec. is

$$\frac{L\omega}{R} = \frac{0{\cdot}5 \times 2\pi \times 50}{15{\cdot}25} = 10{\cdot}3$$

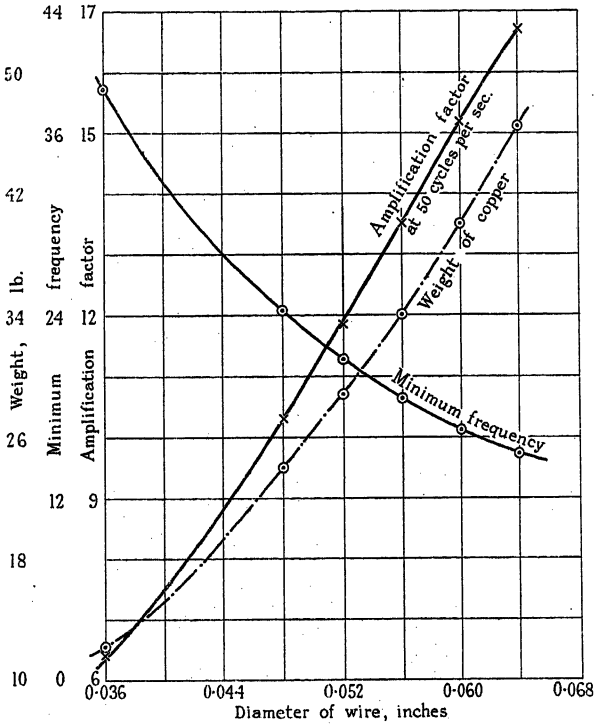


FIG. 6.

and the amplification factor exceeds 5 for frequencies above 24.

By a similar procedure the characteristics of coils wound with wire of various diameters may be examined. The constants for a number of such coils are given in Table 5.

TABLE 5.

	0·036 in. (No. 20 S.W.G.)	0·048 in. (No. 18 S.W.G.)	0·052 in.	0·056 in. (No. 17 S.W.G.)	0·060 in.	0·064 in. (No. 16 S.W.G.)
d' (= diameter of d.c.c. wire, in mm) ..	1·164	1·473	1·571	1·672	1·774	1·875
N (= number of turns)	1 700	1 550	1 510	1 470	1 435	1 405
D (= diameter of coil, in cm)	17·7	21·5	22·6	23·7	24·8	26·0
l (= total length of wire, in metres) ..	950	1 050	1 072	1 095	1 117	1 144
R (= resistance of coil, in ohms)	24·45	15·25	13·25	11·65	10·35	9·44
Amplification factor at 50 cycles per sec. ..	6·42	10·3	11·85	13·47	15·17	16·63
Minimum frequency for an amplification factor of 5	39·0	24·3	21·1	18·6	16·5	15·0
Weight of copper, in lb.	12·2	24·0	28·8	34·1	40·0	46·5

In Fig. 6 curves are plotted to show the variation with the gauge of wire of (*a*) weight of coil, (*b*) amplification factor at 50 cycles per sec., and (*c*) lowest frequency at which the amplification factor exceeds 5.

These curves are of assistance in deciding upon the gauge of wire with which to wind the coil. A compromise must clearly be made between a heavy coil of high amplification factor and a light coil of low amplification factor.

A suitable size of wire to employ for the 0·5-henry coil would be 0·054 in. This size having been decided upon, the details of the coil may be calculated by the method given above. The figures obtained are:—

Number of turns	= 1 490
Diameter of coil	= 23·15 cm
Total length of wire	= 1 083 m
Resistance of coil	= 12·55 ohms
Amplification factor at 50 cycles per sec.	= 12·5
Minimum frequency for an amplification factor of 5	= 20
Weight of copper	= 31·7 lb.

Such a coil would be of small bulk, and the analyser in which it was incorporated would have the advantage of being semi-portable.

APPENDIX II.

Specimen Observation Sheet.

Date. Wave-Form.

Frequency = 100 Circuit resistance = $10{\cdot}8_0$ ohms

Inductance of coil = $0{\cdot}33_2$ henry Amplification factor ($L\omega/R$) = 19·3

Order of harmonic	R_1 (ohms)	R_2 (ohms)	Terminal voltage (E)	Deflection of thermionic voltmeter	Volts measured	Coil voltage (E_L)	Magnitude of harmonic (E_m)	E_m/E	E_m as percentage of fundamental
	× 10^{-5}	× 10^{-5}	volts					per cent	
3	10·4	1·4	$23{\cdot}4_0$	129·8	3·73	$27{\cdot}7_0$	0·478	$2{\cdot}04_0$	$2{\cdot}06_0$
5	10·1	0·1	$23{\cdot}4_0$	95·4	2·76	275·0	$2{\cdot}85_0$	12·17	12·30
7	10·2	0·2	$23{\cdot}4_6$	108·4	3·05	155·5	$1{\cdot}11_5$	$4{\cdot}75_0$	4·80
9	10·2	0·2	$23{\cdot}4_6$	89·7	2·60	132·8	$0{\cdot}76_6$	$3{\cdot}26_5$	3·30
11	10·2	0·2	$23{\cdot}4_0$	122·8	3·35	171·0	$0{\cdot}80_6$	$3{\cdot}44_5$	3·48
13	10·5	0·5	$35{\cdot}7_0$	140·2	3·65	76·3	$0{\cdot}30_4$	0·852	0·861
15	10·7	0·7	$35{\cdot}7_0$	147·3	3·75	57·3	0·198	0·554	0·560
17	10·8	2·8	$35{\cdot}7_6$	125·7	3·40	$13{\cdot}1_2$	$0{\cdot}040_6$	$0{\cdot}113_8$	$0{\cdot}115_0$
19	10·9	1·9	$35{\cdot}7_6$	130·6	3·49	$20{\cdot}0_4$	0·0547	$0{\cdot}153_4$	$0{\cdot}155_0$
21	10·8	1·8	$35{\cdot}7_6$	142·8	3·69	22·14	$0{\cdot}054_7$	$0{\cdot}153_4$	$0{\cdot}155_0$
23	10·8	2·8	$35{\cdot}8_2$	142·1	3·68	14·20	0·0320	0·0891	0·0900
25	10·0	8·0	$35{\cdot}8_2$	135·3	3·57	4·46	0·00923	$0{\cdot}0257_5$	0·0260
27	10·0	6·0	$35{\cdot}8_2$	141·4	3·67	$6{\cdot}1_2$	$0{\cdot}0117_5$	$0{\cdot}0327_5$	0·0331
37	10·0	10·0	$35{\cdot}8_2$	108·0	3·04	$3{\cdot}0_4$	$0{\cdot}0042_6$	$0{\cdot}0118_8$	0·0120

The value of the measured voltage is read off from the calibration curve of the thermionic voltmeter.

Then $E_L = R_1/R_2$ = measured voltage

and $E_m = E_L/19{\cdot}3m = 0{\cdot}0518E_L/m$

The magnitude of the fundamental as calculated from a knowledge of the harmonics is 99·0 per cent of the effective value.

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THE CAPACITANCE OF A GUARD-RING SPHERE-GAP.*

By G. YOGANANDAM, B.E., Graduate.

(*Paper received 23rd November*, 1931.)

SUMMARY.

Formulæ for the capacitance of a guard-ring sphere-gap are derived by the method due to G. R. Dean (*Physical Review*, 1913, vol. 1, p. 316) in which a solution of Laplace's equation is employed, and also by the well-known method of point charges (A. RUSSELL, "Alternating Currents," vol. 1, p. 236). Expressions suitable for computation are given for the practical case of equal spheres. A few numerical examples are also given, together with the measured values of the capacitance of a 50-cm guard-ring sphere-gap.

INTRODUCTION.

An important use of the guard-ring sphere-gap is the measurement of high crest voltages, with the aid of a rectifier circuit. In high-tension bridge measurements the gap finds an equally important application as a standard capacitance. In the author's opinion these applications amply justify the predetermination of the capacitance of such a gap. The problem of two electrified spheres has been almost completely solved by Dr. Alexander Russell, and it is chiefly with the help of his formulæ for the capacitance coefficients that the author has derived expressions for the capacitance of the guard-ring sphere-gap.

DERIVATION OF FORMULÆ.

The capacitance of a guard-ring sphere-gap may be defined as the charge on the spherical cap forming part

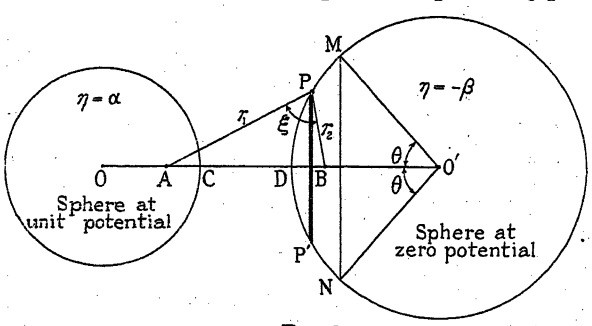


FIG. 1.

A and B are the inverse points.
$AB = 2r$.
In bipolar co-ordinates about A and B the equations to the circles which are the projections of the spheres are $\eta = \alpha$ and $\eta = -\beta$, where $\eta = \log_e r_2/r_1$; $OO' = c$; $CD = d$; $OC = a$; $O'D = b$; $\omega = \alpha + \beta$.

of the sphere which is kept at zero potential, the other sphere being at unit potential.

Method 1.—Referring to Fig. 1, let the sphere ($\eta = -\beta$) be at zero potential, while the other sphere is maintained at unit potential. Then by Dean's method, the charge on the circular elementary area, shown shaded in Fig. 1, is given by

$$dQ = -\frac{r}{2}\sum_{m=0}^{m=\infty}(2m+1)\,\mathrm{cosech}\,(m+\tfrac{1}{2})\,.\,\omega e^{-(m+\frac{1}{2})\alpha}\,\frac{P_m(\cos\xi)\sin\xi d\xi}{\sqrt{[2(\cosh\beta-\cos\xi)]}} \quad . \quad (1)$$

The charge on the spherical cap MDN is therefore given by

$$K = -\frac{r}{2}\sum_{0}^{\infty}\left[k_m\left\{\gamma P_m(\mu)+\frac{\gamma^3}{1.3}P'_m(\mu)+\frac{\gamma^5}{1.3.5}P''_m(\mu)+\ldots\frac{\gamma^{2m+1}}{1.3\ldots(2m+1)}\cdot\frac{d^nP_m(\mu)}{d\mu^n}\right\}\right]_{\mu}^{\mu=-1} \quad . \quad (2)$$

where $\dfrac{d^nP_m(\mu)}{d\mu^n}$

$$= \frac{(m+n)!}{2^m m!(m-n)!}F[n-m,\ n+m+1,\ n+1,\ \tfrac{1}{2}(1-\mu)]$$

$$k_m = (2m+1)\,\mathrm{cosech}\,(m+\tfrac{1}{2})\omega\,.\,e^{-(m+\frac{1}{2})\alpha}$$

$$\gamma = \sqrt{[2(\cosh\beta-\mu)]},\ \text{and}\ \mu = \cos\xi = \frac{1-\cosh\beta\cos\theta}{\cosh\beta-\cos\theta}$$

Putting $\lambda = \sqrt{[2(\cosh\beta+1)]}$, (2) may be written thus:—

$$K = -\tfrac{1}{2}r[k_0(\lambda-\gamma)+k_1(-\lambda+\tfrac{1}{3}\lambda^3-\gamma\mu-\tfrac{1}{3}\gamma^3) + k_2(\lambda-\lambda^3+\tfrac{1}{5}\lambda^5-\gamma\frac{3\mu^2-1}{2}-\gamma^3\mu-\tfrac{1}{5}\gamma^5) + \ldots] \quad . \quad (3)$$

Equal Spheres.—When the spheres are equal we have $\alpha = \beta$ and $\omega = 2\alpha$. The above series is rapidly convergent for large values of α, and is suitable for computation when α or d/a is greater than unity.

For example, if $\alpha = 1$ ($d/a = 1{\cdot}0862$) and $\theta = 33°$,

$$K = -0{\cdot}58760\alpha(0{\cdot}14194 - 0{\cdot}01290 + 0{\cdot}00044\ldots) = -0{\cdot}07608\alpha$$

If the spheres are very close together, the following formula gives approximate results:—

$$K = \frac{a}{4}\log_e\frac{2}{\cosh\beta-\mu} \quad . \quad . \quad . \quad . \quad (4)$$

For example, if $d/a = d/b = 0{\cdot}0001$, and $\theta = 33°$,

$$K = -2{\cdot}02a$$

($2{\cdot}03a$ is nearer the correct value.)

For the case of equal spheres, expanding each term in

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equation (1) in powers of $e^{-\alpha}(=x)$, and making use of the relation

$$\sum_0^\infty (2m+1)x^m P_m(\mu) = \frac{1-x^2}{(1+x^2-2x\mu)^{3/2}}$$

it can be shown, after regrouping the terms and simplifying, that the capacitance of the sphere-gap is given by

$$K = -\tfrac{1}{2}[k_{1.1} - k_{1.2}] + r\gamma\left[\frac{\sinh 3\alpha}{(\cosh 3\alpha - \cosh\alpha)(\cosh 3\alpha - \mu)^{\frac{1}{2}}} + \frac{\sinh 7\alpha}{(\cosh 7\alpha - \cosh\alpha)(\cosh 7\alpha - \mu)^{\frac{1}{2}}} \cdots\right] \quad (5)$$

where $k_{1.1}$ and $k_{1.2}$ are the capacitance coefficients of the spheres. It will be shown that the above expression is identical with the following expressions derived by the method of point charges.

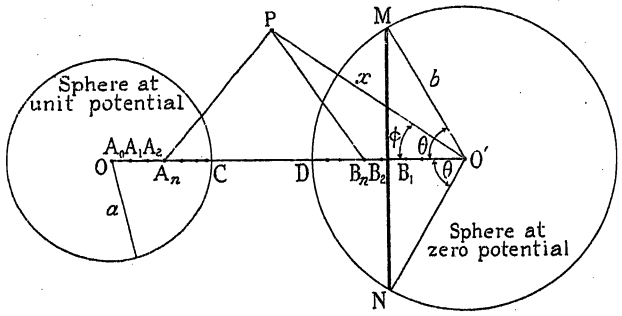


FIG. 2.

$q_0, q_1, q_2 \ldots q_n \ldots$ and $q_1', q_2', q_3' \ldots q_n' \ldots$ are point charges placed at $A_0, A_1, \ldots A_n$, and $B_1, B_2, \ldots B_n$, respectively.

$$O'P = x, \quad OA_n = A_n = \frac{a\sinh n\omega}{\sinh(n\omega+\alpha)} \quad O'B_n = b_n = \frac{b\cdot\sinh[(n-1)\omega+\beta]}{\sinh n\omega}$$

$$q_n = \frac{a\sinh\alpha}{\sinh(n\omega+\alpha)}; \quad q_n' = -\frac{a\sinh\alpha}{\sinh n\omega} \quad \omega = \alpha+\beta.$$

$(c-b_n)a_n = a^2$; $(c-a_{n-1})b_n = b^2$. Other data as in Fig. 1.

Method 2.—Following the method of point charges (see Fig. 2), the potential at any point P is given by

$$V = \sum_{n=1}^{n=\infty}\left[\frac{q_n'}{(x^2+b_n^2-2xb_n\cos\phi)^{\frac{1}{2}}} + \frac{q_{n-1}}{[x^2+(c-a_{n-1})^2-2x(c-a_{n-1})\cos\phi]^{\frac{1}{2}}}\right]$$

and the electric force on the surface of the sphere of radius b is given by

$$\left(\frac{dv}{dx}\right)_{x=b} = \sum_{n=1}^{n=\infty}\left[-\frac{q_n'(b-b_n\cos\phi)}{(b^2+b_n^2-2bb_n\cos\phi)^{3/2}} - \frac{q_n[b-(c-a_{n-1})\cos\phi]}{[b^2+(c-a_{n-1})^2-2b(c-a_{n-1})\cos\phi]^{3/2}}\right]$$

The capacitance of the guard-ring sphere-gap is therefore given by

$$K = \int_0^\theta -\frac{1}{4\pi}\left(\frac{dv}{dx}\right)_{x=b} \cdot 2\pi b\sin\phi \cdot d\phi$$

$$= \tfrac{1}{2}\left[\sum_1^\infty \frac{q_{n-1}+q_n'}{(1-p_n\cos^2\frac{1}{2}\theta)^{\frac{1}{2}}}\right] - \frac{k_{1.1}-k_{1.2}}{2} \quad (6)$$

where $p_n = \dfrac{4r_n}{(1+r_n)^2}$, and $r_n = \dfrac{b_n}{b}$

The above expression will be identical with (5) if we substitute

$$\frac{1-\mu\cosh\alpha}{\cosh\alpha-\mu} = \cos\theta$$

The series within brackets is rapidly convergent only for large values of $(c-a-b)$, and for such values the following formula may be used:—

$$K = -\frac{k_{1.1}-k_{1.2}}{2} + \tfrac{1}{2}(1-p_0\cos^2\tfrac{1}{2}\theta)^{-\frac{1}{2}}\left[k_{1.1}+k_{1.2}-(q_0+q_1')\delta_1-(q_1+q_2')\delta_2\ldots\right] \quad (7)$$

where $p_0 = \dfrac{4e^{-\beta}}{(1+e^{-\beta})^2} = \operatorname{sech}^2\dfrac{\beta}{2}$,

and $\delta_n = 1-\left(\dfrac{1-p_0\cos^2\frac{1}{2}\theta}{1-p_n\cos^2\frac{1}{2}\theta}\right)^{\frac{1}{2}}$

Even when d is small compared with a or b, the above series is sufficiently convergent for practical purposes, and is suitable for computation in the slightly different form given below.

$$K = -\frac{k_{1.1}-k_{1.2}}{2} + \frac{k_{1.1}+k_{1.2}-\sum_{n=1}^{n=n}(q_{n-1}+q_n')}{2(1-p_0\cos^2\frac{1}{2}\theta)^{\frac{1}{2}}} + \tfrac{1}{2}\sum_1^n \frac{q_{n-1}+q_n'}{(1-p_n\cos^2\frac{1}{2}\theta)^{\frac{1}{2}}} \quad (8)$$

$k_{1.1}$ and $k_{1.2}$ in the above expressions are easily computed to a high degree of accuracy by the formulæ given by Alexander Russell.*

The formulæ for the particular case of equal spheres are given in the Appendix to this paper.

Equal Spheres.—When the spheres are equal and $d/a < 0{\cdot}5$, formula (7) may be used. For example, with $\alpha = \beta = 1$ and $\theta = 33°$,

$$K = \tfrac{1}{2}a\left[-1{\cdot}50943+0{\cdot}27700^{-\frac{1}{2}}\left\{0{\cdot}76180-0{\cdot}04735-0{\cdot}000094\ldots\right\}\right] = -0{\cdot}07608a \quad (a)$$

which agrees with the result given by (3).

If $d/a < 0{\cdot}1$, taking the first three terms of the series in (8) involves a maximum inaccuracy of less than 1 part in 1 000, while 4 terms give an accuracy of at least 2 parts in 10 000. The accuracy is greater for higher values of d/a. For example, if $a = 0{\cdot}3$ ($d/a = 0{\cdot}09066$) and $\theta = 33°$,

$$K = -0{\cdot}3959a \quad (b)$$

If the spheres are almost touching, the following formula gives an accuracy of 1 part in 1 000, provided that θ is not very small:—

$$K = -\frac{k_{1.1}-k_{1.2}}{2} + \frac{a}{2}\left[\frac{0{\cdot}1530}{(c/a-2\cos\theta)^{\frac{1}{2}}} + \frac{1{\cdot}500}{(5-4\cos\theta)^{\frac{1}{2}}} + \frac{0{\cdot}5833}{(25-24\cos\theta)^{\frac{1}{2}}} + \frac{0{\cdot}3667}{(61-60\cos\theta)^{\frac{1}{2}}}\right] \quad (9)$$

For example, when $a = 0{\cdot}01$ and $\theta = 33°$,

$$K = -2{\cdot}031a$$

* A. RUSSELL: "Alternating Currents," vol. 1, pp. 239-243; and *Proceedings of the Physical Society of London*, 1922-23, vol. 35, pp. 18-19.

Experimental Results.—The capacitance of a 50-cm guard-ring sphere-gap supplied by Messrs. Emile Haefely and Co. (the earthed electrode is only a hemisphere and $\theta = 33°$ approximately) was measured with the high-voltage Schering bridge for two values of a, viz. 0·3 and 1, and values of 11·1 $\mu\mu$F and 2·17 $\mu\mu$F respectively were obtained, while expressions (*a*) and (*b*) give 10·99 $\mu\mu$F and 2·11 $\mu\mu$F respectively.

It is seen that the formulæ given above yield results which are sufficiently in agreement with the observed values to be of practical utility.

Appendix.

The following formulæ due to Dr. Alexander Russell may be used for the evaluation of $k_{1.1} - k_{1.2}$ and $k_{1.1} + k_{1.2}$ in the case of equal spheres.

(*a*) If $d/a < 0{\cdot}1$,

$$k_{1.1} - k_{1.2} = \frac{a}{2}\left(1 + \frac{d}{6a}\right)\left(2{\cdot}5407 + \log_e \frac{a}{d} + \frac{d}{9a}\right)$$

$$k_{1.1} + k_{1.2} = \frac{a}{2}\left(1 + \frac{d}{6a}\right)\left(1{\cdot}3863 - \frac{d}{12a}\right)$$

The accuracy of these formulæ is 1 in 10 000.

(*b*) If $1 > d/a > 0{\cdot}1$,

$$k_{1.1} - k_{1.2} = a\left[1 + \frac{a}{c} + x^2(1-x^2)\left\{\frac{1}{1-x} + \frac{x^6}{1-x^3} + \frac{x^{12}}{1-x^5}\cdots\right\}\right]$$

$$k_{1.1} - k_{1.2} = a\left[1 - \frac{a}{c} + x^2(1-x^2)\left\{\frac{1}{1+x} + \frac{x^6}{1+x^3} + \frac{x^{12}}{1+x^5}\cdots\right\}\right]$$

where $x = e^{-a}$.

(*c*) If $d/a > 1$,

$$k_{1.1} - k_{1.2} = a\left(1 + \frac{1}{\xi} + \frac{1}{\xi^2} - \frac{1}{\xi^8} + \frac{1}{\xi^3 - 2\xi^2 + \xi - 1}\right)$$

$$k_{1.1} + k_{1.2} = a\left(1 - \frac{1}{\xi} + \frac{1}{\xi^2} - \frac{1}{\xi^8} + \frac{1}{\xi^3 + 2\xi^2 + \xi + 1}\right)$$

where $\xi = c/a$.

The accuracy of these formulæ is 1 in 10 000.

DISCUSSION ON

"THE TECHNIQUE OF THE HIGH-SPEED CATHODE-RAY OSCILLOGRAPH."*

Dr. J. L. Miller (*communicated*): Since the advent of the original Dufour oscillograph, several others of somewhat similar type have been developed by independent workers. These, having been designed with different ends in view, vary considerably even in their major points, and probably no two laboratories have the same oscillograph equipment. This is particularly the case as regards the timing and synchronization circuits. The authors, in their valuable contribution to the technique of cathode-ray oscillography, have described in more than usual detail the methods they adopted in overcoming their difficulties, and the variations best suited to their own requirements. In fact, as one who has been engaged recently in the development of a high-voltage cathode-ray oscillograph in the Ferranti Research Laboratories, I am fully conversant with the difficulties and pitfalls, and I feel that the authors are to be congratulated on their very successful researches. Our oscillograph, during its development, gave rise to many of the problems described by the authors. In some cases the solution was similar to that adopted by them, while in other cases the final result was quite different. Dealing with discharge tubes first, we have experienced with our own glass tubes most of the difficulties described by the authors, and, in fact, I am rather relieved to know that they have happened to other people. We overcame our heating problems by water-cooling the anode and arranging for a quick stream of compressed air to flow round a duct in the cathode and cathode stem. With our glass discharge tubes, we generally use a discharge current of 1 mA, and we once had the experience of a tube which normally would run at anything between 0 and 4 mA, but which on certain occasions would run only below 1 mA, and yet on other occasions would run only above 1 mA. In the latter two cases outside the temporary range of operation the cathode ray was unsteady, and the discharge tube adjacent to the cathode was brightly lit up. The trouble here was found to be due to the presence of foreign vapours in the apparatus, the effect being controlled to some extent by the temperature. With regard to the general design of discharge tubes, we find it advantageous so to dispose the insulation about the cathode that a highly concentrated pre-anode beam results. The requisite post-anode energy can then be obtained with the minimum size of anode hole, and this directly assists in obtaining the smallest spot. The glass discharge tube used in obtaining the oscillogram shown in Fig. A was designed with this principle in view, and it is seen that a fine trace results. In addition to our glass discharge tube, with which all our previous work has been done, we have an experimental tube whose cathode is surrounded by a shaped metal cup. The latter is insulated from the cathode and runs at

* Paper by Messrs. F. P. Burch and R. V. Whelpton (see page 880).

free potential, yielding a highly concentrated beam. With this arrangement, for the same size of anode hole and for the same post-anode current, the discharge current is about one-tenth that required with the glass discharge tube; a feature of this tube is that it will run satisfactorily at low values of discharge current, thus minimizing heating difficulties. It will operate, if desired, with the cup at cathode potential, but a loss of concentration results. The high efficiency, the shielding of all insulation from bombardment and high electric stress, and the stabilizing effect of a conducting shield surrounding the cathode, are strong points in favour of the use of such a design. I should be interested to know whether the authors have tried such an arrangement in conjunction with their own tube. The authors state that they run their tube at 40 to 45 kV, and I

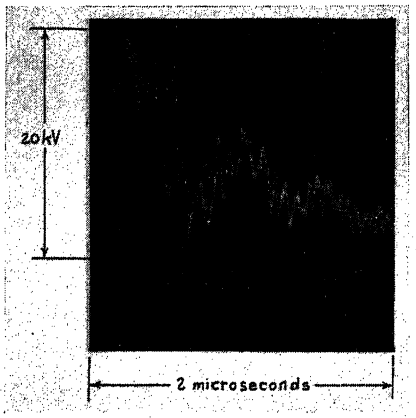


FIG. A.

should be interested to know whether the design shown in Fig. 2 will operate at, say, 55 kV, or whether 45 kV is its limit. For phenomena having a total duration of 10^{-7} sec., say, we find it desirable to use about 55 kV, although admittedly for transformer and insulator work such high speeds are normally needless. To be able to record down to 10^{-8} sec., however, is useful when carrying out work on the oscillograph's own sweeping and tripping circuits, and for such purposes I am of the opinion that a voltage somewhat greater than 45 kV is desirable. In this connection it would be interesting to know the value of the current in the post-anode beam in the authors' oscillograph. In our case a few micro-amperes serve to give a very satisfactory trace. For very long transients it would be interesting to know whether the authors take any steps to reduce the post-anode beam current. This question arises out of the fact that the trace in Fig. 9, which is the longest time-base shown, is a little thicker than in the other records. As was pointed out in a previous discussion, we prevent fogging of the photographic plate by means of a trap which releases and withdraws the ray at the beginning and end of the records. Ours differs from the authors', however, in that we use only one set of plates and two diaphragms, and this simpler arrangement helps to keep down the total length of the oscillograph. In our case the total length from the base to the anode is 85 cm, compared with the authors' 151 cm, and this has certain, though not necessarily marked, advantages. Some time ago we considered the possibility of employing a double-plate system, but refrained from doing so in view of the fact that increase in capacitance and the addition of further resistance by increasing the time-constant of the circuit might nullify the advantages gained. Having had no experience of the arrangement it is difficult to know which method is preferable, but if the authors have used a single-plate system as well perhaps they would give their views. The system used by us fulfils our own requirements. Regarding the authors' remarks on electric and magnetic fields in opposition, we too have observed loss of definition from this cause, and recently the difficulty has been avoided by providing the plate holder with mechanical movement in two directions, so that the zero position of the beam can be brought to any desired position on the photographic plate. The movement is effected from outside the vacuum. In this way the definition of the trace is maintained and distortion prevented in cases where normally a strong constant magnetic field would be used to bias the trace; for instance, one sometimes wants to put a timing oscillation on the edge of the plate so that it will not interfere with the rest of the oscillogram. Many other cases arise. Regarding the authors' statement that they preferred to treat every artificial surge as "uncontrolled," I am of the opinion that in a laboratory where the surge can be "controlled" their method introduces avoidable complication in a part of the equipment where as much simplicity as possible is desirable. It would be interesting, therefore, if the authors gave, at any rate, some of the reasons which led them to adopt this method of operation. We use a rather different arrangement. For work up to 20 kV, the same voltage operates the ray release circuit, the sweep circuit, and the transient circuit through a common spark-gap. Time-lag is obtained by a double overhead line having a surge impedance of 450 ohms. One advantage of this arrangement is that, due to the greater simplicity, the three circuits can be so disposed that mutual coupling between them can be practically eliminated, and so far we have found it unnecessary to rely on screening. For higher impulses, the small surge generator is arranged to trip a separate high-voltage surge generator. The delay in this case can be obtained either by placing the double line on the high-voltage side (after Krug) or using it as the connection between the low- and high-voltage generators. In this way the oscillograph with its equipment is very flexible and is capable of being used on probably every type of problem, with the exception of artificial or real lightning investigations on transmission lines.

Messrs. F. P. Burch and R. V. Whelpton (*in reply*): The irregular behaviour of a discharge tube mentioned by Dr. Miller is interesting; we have not experienced anything exactly like it. We have had instability due to the decomposition of grease or fluff, with consequent evolution of large quantities of vapour, but our experience has not led us to suppose that a moderate and steady pressure of foreign vapour would be harmful. We have not used the arrangement of an insulated metal cup surrounding the cathode. In many, probably most, of our oscillograms, the spot on the

film is the focused image, not of the 1-mm anode hole, but of the narrowest section of the cathode-ray beam, wherever that may be (perhaps at the cathode, perhaps in the neighbourhood of the anode). The fineness of the trace then depends to a great extent on the age (i.e. the amount of pitting) of the cathode. In this connection reference should be made to the discovery by de Laszlo and Cosslett* that the beam from an aged cathode has a hollow structure with a central core. This is, no doubt, the explanation of the fact that the trace of the timing wave in our Fig. 8 is double, and that we have had many traces which consist of three fine lines close together. With regard to the general question of beam intensity, we consider that a fuller investigation is desirable both of the electrostatic focusing action, and of the diameter of the beam at its narrowest point, in tubes such as that shown in our Fig. 2 and the arrangement with the cathode hood used by Dr. Miller. The tube shown in Fig. 2 operates stably from 8·5 kV to 60 kV (the highest voltage tried), and with currents from 0·3 mA or less up to several milliamperes. The electron current reaching the photographic film depends, of course, on the angular diameter of the beam selected by the central diaphragm; with a beam of 0·009 radian and a discharge current of 1 mA the current in the recording spot is 28 μA at a cathode voltage of 42·5 kV, and 35 μA at 60 kV. With 45 kV and 1 mA we have recorded oscillations of 4·5-m wavelength. Except for the highest speeds it is certainly desirable to reduce the post-anode beam current; as Dr. Miller surmises, this was not done in Fig. 9.

We have not made a thorough trial of a beam-trap having one pair of plates only, and are interested to learn that Dr. Miller finds it satisfactory. The two-stage trap commended itself to us partly because of the completeness of trapping of stray electrons, but principally because when the plates are cross-connected, after Gábor, a small voltage, insufficient to trap, gives no resultant deflection. Thus the distorting effects of oscillatory currents in the trip circuit, which sometimes manifest themselves at the very beginning of the record, are reduced to a minimum. The length of our oscillograph was determined, not by the length of the beam-trap, but by the high deflectional sensitivity required, combined with the fact that we wished to place the focusing coil midway between anode and film—Busch's condition for the sharpest focus.* If very high writing speeds were not desired, a beam of small angular divergence could be used. One could then depart from Busch's condition, bringing the discharge tube nearer to the focusing coil. The length of the oscillograph could thus be reduced by an amount depending on the angular aperture required in the beam and the loss of focus permissible. It is possible that these factors, and not the length of the beam-trap, would set the limit. Our own instrument could be shortened by some 30 cm before a single-stage trap became necessary.

We cannot agree with Dr. Miller that it is preferable to treat laboratory surges as "controlled." Certainly when the voltage of the surge is of the same order as the sweep-deflection voltage this method is simpler, but this is seldom the case in practical work. The 1 000-kV impulse generator which represented our principal problem has four stages only. To "control" it would require the application of an impulse sufficient to trip with certainty a pre-stressed 250-kV gap. At least 50 kV—probably 100 kV—would be needed. The circuits would certainly be no simpler in principle than those which we use, and being of high voltage they would be enormously bulkier and more expensive. This consideration, together with the conviction that we should sooner or later require to record some phenomenon which could not possibly be "controlled," decided us in favour of the "automatic" method of working. The latter conviction has been justified; we have had occasion to investigate the behaviour of the voltage in the fraction of a microsecond immediately preceding a 50-cycle spark-over.

* *Nature*, 1932, vol. 130, p. 59.

* *Archiv für Elektrotechnik*, 1927, vol. 18, p. 583.

INSTITUTION NOTES.

Summer Meeting, 1933.

The Council have cordially accepted an invitation from the Committee of the Western Local Centre to hold the next Summer Meeting in that district. Full particulars will be circulated in due course to all members.

Electrical Engineers' Ball.

The next Electrical Engineers' Ball will be held at Grosvenor House, Park Lane, W., on Friday, 17th February, 1933, the day after the Annual Dinner of the Institution. Any surplus that may be available after defraying the cost of the function will be handed over to the I.E.E. Benevolent Fund. The Committee of that Fund, under whose auspices the function will in future be managed, will have the co-operation of the former Ball Committee, and the detailed arrangements for the forthcoming Ball will be in the hands of an Executive Committee consisting of representatives of the Benevolent Fund Committee and of the Ball Committee. The function, which should not be confused with the Ball to be held on the 18th November by the Electrical Trades Benevolent Institution, will be on the same lines as those of the previous Electrical Engineers' Balls. These have in the past been so well attended that the demand for tickets has always exceeded the number available. The arrangements for the distribution of tickets on the present occasion will be announced later.

Conversazione of Overseas Members.

A conversazione of members from overseas and their ladies was held at the Institution on Wednesday, the 22nd June last. About 120 members and ladies were present.

After a reception by the President and Council, short addresses dealing with recent developments in electrical progress in Great Britain were delivered in the Lecture Theatre by Sir Archibald Page (Past-President) on "The Grid," Sir Thomas F. Purves (Past-President) on "Transatlantic Telephony," and Mr. Noel Ashbridge (Chief Engineer of the B.B.C.) on "Broadcasting To-day." The proceedings concluded with a reunion in the Library.

Among those who accepted the Council's invitation were the following: Mr. J. W. Atkins (India), Mr. J. Aylmer (Ceylon), Mr. M. Barr (U.S.A.), Mr. J. W. A. Binner (Colombia, S. America), Mr. F. Brand (Federated Malay States), Mr. W. K. Brasher (Iraq), Mr. H. S. Bulley (India), Major W. H. C. Coates (India), Mr. J. Hardman (Johore, Malay), Mr. E. Harper (Ceylon), Mr. R. Heath (India), Mr. C. S. Jeffrey (Australia), Mr. F. E. Kennard (Ceylon), Mr. H. J. Loughlin (India), Mr. C. H. Mellor (China), Mr. P. L. Newman (New Zealand), Mr. F. L. Otter (India), Mr. G. R. Paine (Australia), Mr. Bernard Price (Transvaal), Mr. A. B. Raworth (China), Mr. C. G. Seeley (Australia), Mr. J. H. Waters (India), Mr. D. P. Welman (British West Indies), Mr. J. S. Whitney (China), Mr. W. L. Whyte (Federated Malay States), Mr. R. A. Williams (China), Mr. H. D. Wolstenholme (Australia), and Mr. R. F. Woods (India).

It is proposed to hold similar functions in future years in May or June, and members from overseas likely to be in this country about that time are requested to notify the Secretary in order that they may be supplied with particulars of the arrangements.

Discussions at Meetings.

The Council desire again to remind the members that verbal contributions to the discussions at meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a "discussion," and that contributions in manuscript should, more appropriately, be sent to the Secretary for publication in the *Journal* as "communicated remarks."

Annual Tables of Constants and Numerical Data.

Constants and data relating to the subjects of Electricity, Magnetism, and Electrochemistry, have just been reprinted from Volumes VIII (1927–1928) and IX (1929) of the above Tables, all explanations being given in both English and French. The reprint consists of over 500 pages, and members of the Institution can obtain bound copies at a reduced price of £1 14s. (instead of £2 5s.). All orders and inquiries should be sent to Dr. Charles Marie, 9 Rue de Bagneux, Paris VIe.

Engineers' German Circle.

The Engineers' German Circle (Deutscher Ingenieurzirkel in London) was formed in 1931, with the joint support of the Institution of Mechanical Engineers and of the Verein Deutscher Ingenieure, to further the study of technical German, to give opportunities of hearing lectures in German by eminent German-speaking technical men, and to bring together engineers interested in Continental technical developments. Meetings are held at the Institution of Mechanical Engineers about once every four weeks during the session, on Mondays at 6 p.m. Members meet for tea and social intercourse from 5.15 p.m. The lectures are, as far as possible, illustrated with lantern slides, in order to help the members to understand better the technical terms involved; and as a rule, they last about 40 minutes, which allows time for a short discussion in German to follow. The lecturers are asked to use simple language and to speak slowly for the benefit of those not very familar with German. The present session opened on the 10th October. The subscription to the Circle is 5s. a year, and the Secretary is Mr. H. P. Spratt, Science Museum, London, S.W.7.

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THE TWENTY-THIRD KELVIN LECTURE.

"THE WORK OF OLIVER HEAVISIDE."

By W. E. SUMPNER, D.Sc., Member.

(*Lecture delivered before* THE INSTITUTION, 21*st April*, 1932.)

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(3) Radio waves and matter.
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(6) Conclusion.
Appendix 1. Historical notes.
Appendix 2. The nature of the fluxes in Maxwell's theory.
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(1). THE RANGE OF HEAVISIDE'S WORK.

The Kelvin Lecture of the Institution is usually delivered by an eminent leader in physics, who chooses a subject invariably of great interest to the members, but one not always closely associated with their work. To-night a member of the Institution has been honoured by being asked to give the lecture, and the subject chosen, the work of Heaviside, is one which blends the earliest activity of the Institution, namely, telegraphy, with the latest one, wireless telegraphy and telephony. The subject ranges over the whole of electromagnetic theory and practice, and is too vast to be dealt with in other than a general way.

There is no time to dwell on personal* matters concerning the life and character of Heaviside. I must, however, mention that Heaviside was born in 1850, and that he died a few years ago at the age of 75. His family was eminently telegraphic. He was the nephew of Sir Charles Wheatstone, the inventor of telegraphy. One of his brothers, Mr. A. W. Heaviside, was high up in the telegraphic profession. He himself was engaged for some years in the actual practice and development of telegraphy. All his early papers, from 1872 to 1882, deal with normal problems in telegraphy, such as induction balances, duplex telegraphic circuits, and so on. He appears to have been closely associated with the introduction of quadruplex telegraphy. He retired from practice early, but continued throughout his life to work at telegraphic problems.

Heaviside exemplifies a rare case of the combination of great theoretical and mathematical powers with a bias of mind which was strongly practical. He was entirely self-trained. He found that his work needed mathematics, and he trained himself to be a mathematician. He made himself a physical theorist for the same reason. He was, however, chiefly interested in the practical aspect of signalling problems. He regarded all theoretical work as subsidiary. He was a mathematician at one moment, and a physicist at another, but first and last, and all the time, he was a telegraphist. All his early papers up to 1882 dealt with telegraphic problems by normal methods; but after that date, that is from the age of 32 onwards, he dealt with these problems entirely from the point of view of waves, and therefore as problems in directed radio-telegraphy. Heaviside was the first radio-telegraphist.

His work consists of two main parts: the simplification of Maxwell's theory and the improvement of mathematical methods for use with it; and the design of a transmitting line or cable needed to convey electrical signals perfectly at high speed.

Before dealing with either of these, something must be said about the clearness with which he could express his ideas, either in the English language, or in the language of mathematics. He was a writer of good, vigorous English, often brightened with touches of humour. He chose his words well, and is noted for his resource in suggesting excellent new words to express novel technical quantities coming into prominence. The younger electrical men of to-day hardly realize how many words and phrases now in standard use originated with Heaviside.

A good instance of his clear writing will be found in the first volume of "Electromagnetic Theory," in the form of a chapter of 150 pages descriptive of waves. It is almost free from symbols. A few equations are given to help the wording to make the exact meaning clear, but not such as to require the reader to use any analytical skill. It is the best chapter yet written on electrical waves, and should be read by all interested in wireless work.

Heaviside's descriptive power had a great influence on his life work, since it was his only support in his effort to convince the world that the self-induction of the line was "the long-distance telephoner's best friend." In dealing with his cable problem he laboured under every conceivable disadvantage. He was working entirely alone. He had to solve a mathematical problem so new and difficult that no existing form of analysis was suited to deal with it. He evolved an experimental process which found no favour with mathematicians. It was something which nobody could understand, and which Heaviside himself did not profess to explain. Physicists were keenly interested in Heaviside's work on electromagnetic theory, but naturally left to technical men any applications to practice. The only men whom Heaviside could hope to interest were telegraphists, and in regard to them Heaviside had to struggle against a fixed erroneous belief of the whole profession. Lord Kelvin's pioneer work on ocean telegraphy was highly

* These have been dealt with in an interesting way in Appleyard's "Pioneers of Electrical Communication" (Macmillan and Co.).

scientific and original. It also had the engineering characteristic, that it was made as simple as possible by taking note of every essential point while neglecting anything which did not appreciably affect the result. The self-induction of the line was ignored, and a working principle was reached which came to be known* as the "KR law." For Kelvin's purpose the neglect of self-induction was quite justifiable and in every way admirable; but as signalling at higher and higher speeds became a want, and as the character of the signals altered from the simple dots and dashes of telegraphy to the highly complex signals of telephony, the KR law of Kelvin ceased to apply because it was no longer sufficiently comprehensive. Heaviside advocated the increase of the self-induction of the line, an idea utterly opposed to the prevailing notions of the time. Heaviside's method was obscure, while his formulæ were complex. If he had not possessed the power of making his views clear in simple language, I doubt very much whether during his lifetime the loading coil would have been invented.

He had many friends in the telegraphic profession, and that profession has never lacked men of great scientific ability capable of realizing and of making clear to their less-trained colleagues the significance of Heaviside's results, and that these results were not merely the expression of personal views but were obtained by methodical mathematical argument. Such men are not necessarily found in the most important professional positions,† so as to be able to exert enough influence on a Government department reluctant to try expensive experiments. Heaviside never had the chance to put his theories to the test. He did suggest practical ways of increasing the self-induction of the line several years before they were actually tried in France and in America. His suggestions, after some preliminary experimenting, would have developed into an invention. As things turned out, the loading coil had to be worked out by other hands. Great credit is due to the inventor of that coil, and also to those concerned with the more recent method of coating the wire with permalloy, or mumetal; but Heaviside was greater than the inventor, since he pointed out in advance what the inventor had to invent. As a rule, theory follows practice, explains it, and makes large-scale developments possible. In this case theory had to come before practice. It is hard to see how the loading coil could have developed out of trials made in the dark.

It is needless in addressing the members of the Institution to take up time in explaining the loading coil, or in urging its importance. It is enough to say that wherever telegraphy is known the name of Heaviside is held in honour. It would also be hopeless to attempt in a public address to discuss Heaviside's mathematics in detail, but the general character of this work must be referred to. No other mathematician has striven so hard to make his work simple, short, and direct; to avoid wandering into side issues, and to refrain from a display of mathematical fireworks. He showed great care in the choice of symbols, and in the modes of printing them. From this point of view his work is an admirable example of plain English in mathematical form. Important variables are chosen with simple plain shapes, free from curls and thin lines, and suitable for compact assembly in a formula. Associated constants are grouped as much as possible, and are represented by less-prominent letters. The effect is to make the working clear, and to reduce to a minimum the number of symbols used, and also the resultant call on the memory. What happens in technical publications is usually the exact opposite to this, in spite of the fact that there is special need in engineering work to make the mathematics as clear and simple as possible.

I shall illustrate these points by an example well known to all of us, and, since this is the only example which I propose to introduce into the Lecture, I shall use it also to picture the operator method. I shall thus use the example to illustrate both the clearness and the obscurity of Heaviside's mathematics. His analysis when dealing with Maxwell's theory involved advanced and difficult mathematics, but this is not the part of his work which is said to be obscure. The part which is called obscure is his operator method which uses little more than simple algebra.

Heaviside chooses, of course, a suitable shape* for his symbol for current, and writes the law of rise of current in an inductive circuit as

$$RC + L\frac{dC}{dt} = E \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or as

$$RA + L\dot{A} = E$$

Having written down the differential equation, the first thing he does is to discard the calculus, by using Boole's symbol p for the differentiator. He writes the equation in operator form as

$$(R + Lp)\,C = E \quad . \quad . \quad . \quad . \quad . \quad (2)$$

He next simplifies as much as possible the mode of denoting the engineering constants R, L, and E, by using a for R/L and C_0 for E/R, leading to

$$(1 + p/a)\,C = C_0 \quad . \quad . \quad . \quad . \quad (3)$$

Next, in a way bolder than Boole, he proceeds

$$C = \frac{1}{1 + (p/a)}C_0 = \frac{a}{p}\cdot\frac{1}{1 + (a/p)}C_0 \quad . \quad . \quad (4)$$

$$C = \left(\frac{a}{p} - \frac{a^2}{p^2} + \frac{a^3}{p^3} - \ldots\right)C_0 \quad . \quad . \quad . \quad (5)$$

* The law is called by its historic name. K refers to capacity and R to resistance.

† In one of Heaviside's notebooks now in the possession of the Institution, I found the following lines:—

"Self-induction's 'in the air'
Everywhere, everywhere.
Waves are running to and fro.
There they are, there they go.
Try to stop 'em if you can
You British Engineering man!

Conceive him (if you can)
The Engineering man."

At this point some personal feeling seems to have upset the balance of the bard's rhythm. Other lines are omitted. The "man" may possibly have been very fond of boasting that he "sat at the feet of Faraday." Heaviside remarked that "beetles could do that."

* The International Electrotechnical Commission has settled that the letter I is to be used as the symbol for current. But what is the letter I? No one has decreed how it shall be shaped or printed or pronounced. It appears in many forms, none suitable for assembly in a formula, and the most insignificant of all these forms, a little worm rampant, is the one favoured by the electrical engineer. Its most obvious part is a dot which should not be there, since dots should be reserved for Newton's notation for differentiation.

He now applies his "rule"

$$\frac{1}{p^n} = \frac{t^n}{n!}$$

giving

$$C = C_0\left[a\frac{t}{1} - a^2\frac{t^2}{2!} + a^3\frac{t^3}{3!} - \ldots\right] \quad . \quad . \quad (6)$$

or

$$C = C_0(1 - e^{-at}) \quad . \quad . \quad . \quad . \quad . \quad (7)$$

so that after reintroducing the engineering symbols he gets finally

$$C = \frac{E}{R}(1 - e^{-Rt/L})$$

This has been given at length to show the steps. The calculus equation (1) is changed to the operator equation (2) or (3). The operator is shown in (4) in a closed form, and in (5) when expanded as an infinite series of powers of p. The "rule" is then used to convert to (6), an infinite series in powers of t, which in many cases can be simplified by using a known mathematical function as in (7). The operator in this case is a simple one, but Heaviside treats all operators, however complicated, in the same way, and also applies the same rule, so that the example typifies his method in general. The expansion of the operator, and the use of the rule, are obscure steps, but the actual working is always simple. This example we shall discuss later. We must now consider the first main part of Heaviside's work, electromagnetic theory.

(2). Electromagnetic Theory.

I shall confine myself in this Lecture to Maxwell's theory as applied to ether free from matter. If we cut out from the theory all the laws concerned with matter, the laws which remain are few, simple, and fundamental. Heaviside showed that they could be put in the form of four pairs of laws connecting four pairs of physical quantities, each pair showing perfect symmetry as regards electricity and magnetism. In order to bring out the symmetry I shall use the same symbol, with a distinguishing suffix e or m, to denote the two members of a pair.

The quantities are

Quantity	Electric	Magnetic
Force intensity	$\mathbf{H}_e$	$\mathbf{H}_m$
Flux density	$\mathbf{B}_e$	$\mathbf{B}_m$
Inductivity	e	m
Energy density	T_e	T_m

The four pairs of laws consist of three which are merely descriptive of permanent relations between the above physical quantities, and of a fourth which states the important working laws controlling the changes that take place. They are:—

Law 1. The force-flux law

$$\mathbf{B}_e = e\mathbf{H}_e \qquad \mathbf{B}_m = m\mathbf{H}_m$$

Law 2. The law of continuity

$$\text{div. } \mathbf{B}_e = 0 \qquad \text{div. } \mathbf{B}_m = 0$$

Law 3. The law of energy density

$$T_e = \tfrac{1}{2}H_eB_e \qquad T_m = \tfrac{1}{2}H_mB_m$$

Law 4 (c.c.). The law of cross cutting

$$\left.\begin{matrix}\mathbf{H}_e\\ \mathbf{H}_m\end{matrix}\right\}\left\{\begin{matrix}\text{is the rate at}\\ \text{which the lines of}\end{matrix}\right\}\left.\begin{matrix}\mathbf{B}_m\\ \mathbf{B}_e\end{matrix}\right\}\left\{\begin{matrix}\text{cut unit}\\ \text{length along}\end{matrix}\right\}\left.\begin{matrix}\mathbf{H}_e\\ \mathbf{H}_m\end{matrix}\right\}$$

The quantities e, m, are constants, T is a scalar variable, $\mathbf{H}$ and $\mathbf{B}$ are vectors. $\mathbf{H}$ is reckoned per unit length, $\mathbf{B}$ per unit area of cross-section, and T per unit volume. A vector is denoted by a letter in heavy type, and its tensor by the corresponding letter in italic type. $\mathbf{B}$ is the density of Faraday lines or tubes. The lines $\mathbf{B}_m$ are due to a distant magnet or magnetizing current, and the rate of cutting of $\mathbf{B}_m$ is $\mathbf{H}_e$, the electric force, or e.m.f. per unit length. The lines $\mathbf{B}_e$ are due to distant electric charges whose movements represent one or more currents involving corresponding movements of $\mathbf{B}_e$. The rate of cutting of $\mathbf{B}_e$ is $\mathbf{H}_m$, the magnetic force, or m.m.f. per unit length. In the language of action at a distance, $\mathbf{H}_m$ is said to be due to a remote magnetizing current. In the physical language of Faraday it is due to the local cutting of $\mathbf{B}_e$.

There is much to be said about these laws, but I have only time now to mention some of the points connected with Heaviside's work.

In the first law e and m are not mere numbers. $\mathbf{B}$ and $\mathbf{H}$ differ in physical nature as much as an ampere does from a volt. A current and a voltage may be made numerically equal by adopting suitable units, but no choice of units can possibly make an ampere the same kind of thing as a volt. Heaviside's book is the only one on electromagnetic theory in which the distinction between $\mathbf{B}$ and $\mathbf{H}$ is always kept clear.

Heaviside uses, instead of $\mathbf{B}_e$, Maxwell's displacement symbol $\mathbf{D}$, but points out clearly that "the true analogue of $\mathbf{D}$ is $\mathbf{B}_m$."* Heaviside's $\mathbf{D}$ is a multiple of Maxwell's $\mathbf{D}$, since he adopts what he calls a "rational" system of units, the great advantage of which is that all the important laws can be expressed without containing a needless factor 4π, or $1/(4\pi)$, so that the statement of the laws becomes simpler. In ordinary books the expression for T in law 3 contains a factor $1/(8\pi)$ instead of the factor $\frac{1}{2}$.

The most important point refers to the law of cross cutting, 4 (c.c.). This is not expressed as Heaviside put it. It is stated in a way to show its physical aspect. It needs a little more to make it strictly mathematical. The addition can be made in more than one way. We may express the law in local-action form, or in remote-action (and sum-total) form, involving the idea of action at a distance. This can be illustrated by law 3. The energy density $\frac{1}{2}H_eB_e$ is the local part of the total energy $\frac{1}{2}V \times KV$, where V is the potential between the plates of a condenser whose charge is KV. The Faraday tubes connecting the plates spread out through the whole of space. Maxwell proved that the quantity $\frac{1}{2}H_eB_e$ per unit volume summed up for the whole of space was equal to $\frac{1}{2}KV^2$. He proved a similar relation in connection with the companion law for magnetic energy. Exact ideas about energy are largely due to Kelvin, Helmholtz, and Joule, while most of the laws of energy in sum-total form are due to the work of Kelvin. The principle of the localization of energy is, however, due to Maxwell, and forms one of the two important contributions made by him when developing Faraday's ideas into the electromagnetic theory of light. The other new principle was the concept of dielectric current as the rate of change of displacement $\mathbf{D}$ or $\mathbf{B}_e$. Thus, in dealing with

* "Electromagnetic Theory," vol. 1, p. 105.

law 4, we must remember that the rate of change of $\mathbf{B}_e$ means current density. Now consider the cross cutting law 4 (c.c.). This in its magnetic form is the basis of electrical engineering, and is well known both in its local-action and in its remote-action form. One is the law of the dynamo armature represented in Fig. 1, and the other that of the transformer denoted by Fig. 2.

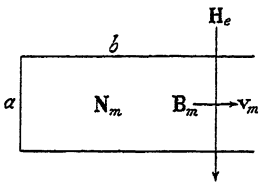


FIG. 1.

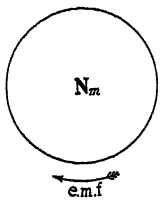


FIG. 2.

$$\text{e.m.f.} = -\dot{\mathbf{N}}_m$$

$$ab\,\mathbf{B}_m = \mathbf{N}_m = \int\int \mathbf{B}_m d\sigma$$

$$\mathbf{H}_e = [\mathbf{B}_m \mathbf{v}_m] \qquad \int \mathbf{H}_e d\lambda = \int\int (-\dot{\mathbf{B}}_m) d\sigma$$

There is no need to explain what is so well known. The point to note is the great physical difference between two laws which are mathematically equivalent. The first gives $\mathbf{H}_e$, a local e.m.f. per unit length, in terms of the movement at velocity $\mathbf{v}_m$ of a local flux density $\mathbf{B}_m$. The second gives a non-localized total e.m.f. in terms of the change of a distant flux $\mathbf{N}_m$.

The former can be expressed as a vector product

$$\mathbf{H}_e = [\mathbf{B}_m \mathbf{v}_m]$$

The latter can be expressed as

$$L_e = \dot{S}_m$$

where L_e is the line integral of H_e round the circuit, and $\dot{S}_m$ is the surface integral of $(-\dot{B}_m)$ over the area bounded by the circuit.

Heaviside, by taking this circuit infinitesimally small, converted the remote-action law into a local-action form and wrote it

$$[\nabla \mathbf{H}_e] \equiv \text{curl}\, \mathbf{H}_e = -\dot{\mathbf{B}}_m$$

We need not consider here the full meaning of this mathematical law.

In the magnetic case there is direct experimental evidence for each form of the law, but in the corresponding electric case, obtained by interchanging the suffixes e and m, the experimental evidence available only applies to the law in remote-action form

$$L_m = \dot{S}_e$$

where L_m is the line integral of the magnetic force $\mathbf{H}_m$ round the circuit, that is the total m.m.f.; and where $\dot{S}_e$ is the surface integral of the current density $\dot{B}_e$ over the area bounded by the circuit, that is the total current represented by "ampere-turns." This is the well-known law of the magnetic circuit, a remote-action law. The corresponding local-action law, though not yet established by direct experiment, is deducible mathematically from the remote-action law in exactly the same way as in the former case. Heaviside was the first to notice the extraordinary fact that Maxwell overlooked this point and was content to leave his laws in the language of action at a distance. Maxwell, with a great ideal before him, took up the ideas of Faraday, examined a chaos of known theories and laws, separated out those which fitted in with Faraday's views from those which did not, and developed the former into his great theory of light. Nearly all these laws were expressed in the language of action at a distance. Maxwell could use them, and was content to use them, in that form. It was Heaviside who introduced what he called the second circuital law in local-action form

$$[\nabla \mathbf{H}_m] \equiv \text{curl}\, \mathbf{H}_m = \dot{\mathbf{B}}_e$$

In doing this he cut out from Maxwell's theory some points which he regarded as not essential, and finally arranged all the fundamental electromagnetic laws in pairs, each of which showed perfect symmetry in regard to electricity and magnetism.

The second circuital law has an equivalent vector form

$$\mathbf{H}_m = [\mathbf{v}_e \mathbf{B}_e]$$

This form of the law was, in essence, recognized both by Heaviside and by Poynting, but neither of them used it in analysis.

The working law of cross cutting [law 4 (c.c.)] can thus be expressed in three equivalent ways, as follows:—

(i) the experimental law in remote-action form as used by Maxwell

$$\int \mathbf{H}_e d\lambda = \int\int (-\dot{\mathbf{B}}_m) d\sigma \quad . \quad . \quad . \quad . \quad (4x)$$
$$\int \mathbf{H}_m d\lambda = \int\int (+\dot{\mathbf{B}}_e) d\sigma$$

(ii) the mathematical local-action law which Heaviside used and called the circuital law

$$[\nabla \mathbf{H}_e] \equiv \text{curl}\, \mathbf{H}_e = -\dot{\mathbf{B}}_m \quad . \quad . \quad . \quad (4c)$$
$$[\nabla \mathbf{H}_m] \equiv \text{curl}\, \mathbf{H}_m = +\dot{\mathbf{B}}_e$$

(iii) the physical local-action law which appears to state exactly the views of Faraday* when expressed in vector form

$$\mathbf{H}_e = [\mathbf{B}_m \mathbf{v}_m] \qquad \mathbf{H}_m = [\mathbf{v}_e \mathbf{B}_e] \quad . \quad . \quad . \quad (4v)$$

Much was done between 1883 and 1885 by Heaviside and by Poynting, working independently, to make clear and to extend Maxwell's theory. Time will not allow of my discussing it in this Lecture, but I have added an historical Appendix dealing with it. The main point to note now is that Heaviside, after arriving at the working law 4 (c), developed from known mathematical theorems an easily workable form of vector algebra particularly suitable for use in connection with it. He did not add anything fundamentally new to Maxwell's theory, or anything in analysis really new mathematically. His work on electromagnetic theory offers a great contrast to that connected with his operator method. Mathematicians have had nothing to say against the one, and nothing to say in favour of the other. They have been very silent on the whole matter.

* "Experimental Researches," vol. 1, p. 529, § 1658.

What Heaviside did was to make the theory so workable that it had the properties of an automatic machine. This sometimes needed the skill of a Heaviside to set it to its task, and sometimes needed the driving power of a Heaviside to make it go. All the same, it was automatic. One end was fed with a mixture of facts and fancies about matter, and out from the other came the results, not as single spies but in battalions. Many of these results were of great interest to the scientific world, and most of the leaders of physics, from Lord Kelvin downwards, discussed them with Heaviside, either personally or through the medium of the scientific Press.

All these problems involved the action of matter, the properties of which are a never-ending source of controversy. This was bad enough in Heaviside's time. It has become far worse since. Nowadays the properties of matter seem to alter every fortnight. Heaviside's results and views were always criticized, but were always treated with great respect. In 1891, Heaviside summed up his work on Maxwell's theory in a single paper printed by the Royal Society in 1892. This was the most important and the most ambitious paper Heaviside ever wrote. It is fairly safe to say that no one yet born has been able to understand it completely. This assertion would be a bold one to make were it not for the fact that there is the great authority of Lord Rayleigh to support it. A letter, now in the possession of the Institution, was written to Heaviside by Lord Rayleigh as Secretary of the Royal Society, when accepting the paper on behalf of the Society, on the 31st October, 1891. To this letter a personal note is added which reads:—"Both our referees, while reporting favourably upon what they could understand, complain of the exceeding stiffness of your paper. One says it is the most difficult he ever tried to read. Do you think you could do anything by illustrations or further explanations, to meet this? As it is, I should fear that no one would take advantage of your work."

The obscurity of the paper does not arise in the mathematics itself, since this, though having a strong Heaviside flavour, is all of standard type and can present no difficulty to the professional mathematician. It is far otherwise with the assumptions underlying the mathematics. These involve numerous physical conceptions for the most part outside the range of experimental evidence, and so abstruse and so little recognized that, however expressed in words, they must be left in such a state that they can be readily misunderstood. The reader can be excused if he fails to follow them. Yet Heaviside was so consistent a man that, if his ideas could be definitely interpreted, his scheme, modified as found necessary, would probably form a firm framework on which permanent physical theories could be built. As it stands, the paper is quoted but rarely, if at all.

We must, however, leave pure theory and proceed to consider Heaviside's application of it to his telegraphic problems.

(3). Radio-Waves and Matter.

Heaviside's object was to design a telegraph cable to transmit signals perfectly at high speed. It is commonly supposed that he solved this problem by means of his operator method. This is only partly true. He used arithmetic as much as algebra, and he used physics more than either. His mathematical result was always an infinite series. This was but natural. It is as unreasonable to expect a mathematical solution to be a simple expression, as to expect the answer to a numerical question to be a simple number such as 3, 4, or 5, instead of a long series of decimals. Solutions given in terms of functions, or of integrals, are all infinite series in disguise. Such solutions are convenient if the functions, or integrals, can be got from tables; otherwise the apparent simplification is little more than a sham. Few seem to realize the large amount of drudgery in numerical calculations which Heaviside went through in order to grasp the meaning of the various forms of infinite series met with in his analysis, or that he made use of every physical argument which he could think of in order to interpret his result. The solution of his problem is to be found, not in his formula, but in his essays. It was by means of these clearly written essays that he at last succeeded in convincing a reluctant telegraphic profession of the truth of his ideas.

He had necessarily to express his problem in terms of coils and condensers and resistances, but he was always thinking in terms of waves. We have thus to consider what the laws have to say about waves.

The laws we need are:—

Law	Electric	Magnetic	
Force-flux	$\mathbf{B}_e = e\mathbf{H}_e$	$\mathbf{B}_m = m\mathbf{H}_m$	(1)
Energy	$T_e = \frac{1}{2}H_eB_e$	$T_m = \frac{1}{2}H_mB_m$	(3)
Cross-cutting	$\mathbf{H}_e = [\mathbf{B}_m\mathbf{v}_m]$	$\mathbf{H}_m = [\mathbf{v}_e\mathbf{B}_e]$	(4v)

We postulate that (i) there is no such thing as action at a distance, and (ii) light waves do not interfere with each other. Light waves received from a particular star are not affected by light emitted by other stars and passed on the journey from the special star. When we look at a star we assume that we see light from that star only, and not a mixture of light from all the stars. The programme of a particular broadcasting station can be reproduced perfectly by a suitable receiver irrespective of the activities of other stations. This could not be the case if the waves merged into one another and lost their separate individuality.

Now suppose that from any cause we have a disturbance represented by two values of H and the corresponding values of B. What happens? We have not to consider action at a distance, or even any other disturbance in the neighbourhood. The laws must thus apply directly to our particular disturbance.

If in (4v) we put one of the velocities, say v_m, equal to zero, it will be seen from (1) and (4v) that all four quantities $\mathbf{B}$, $\mathbf{H}$, vanish. Thus whatever the disturbance may be it must be in motion.*

Next let us assume that it is possible under certain conditions for the electric and magnetic fluxes to move together so that the disturbance moves like a wave of light which remains unchanged as it progresses. We

* This result appears at first to be in conflict with the case of a steady field due either to a permanent magnet, or to a charged condenser. But it can readily be shown that the product of v_e and v_m is always the constant v^2. The two steady cases are the mathematical limits obtained by making one velocity infinite and the other infinitesimal. Thus, if $H_m = M$ and $v_m = cv$, where c and cv are each high infinitesimals, we find $H_e = cv \,.\, mM$, $T_m = \frac{1}{2}mM^2$, and $T_e = c^2T_m$. If $c = 0$, we may have finite values for M and T_m, and yet zero values for v_m, H_e, and T_e.

can find these conditions by putting $\mathbf{v}_e = \mathbf{v}_m = \mathbf{v}$. If no change takes place the two velocities must clearly be the same.

From (1) and (4v) used numerically we find

$$B_e = eH_e = evB_m = evmH_m = emv^2B_e$$

or $$v^2em = 1, \text{ that is } v = (em)^{-\frac{1}{2}}$$

Thus the velocity must be fixed in amount, and from (4v) used vectorially it follows that $\mathbf{H}_e$, $\mathbf{H}_m$, and $\mathbf{v}$, are perpendicular to each other in pairs.

If we use in (3) the value of v found above, we get numerically

$$\tfrac{1}{2}H_eB_e = \tfrac{1}{2}H_mB_m = \frac{1}{2v}H_eH_m$$

This means that the electric and magnetic energy densities are equal, and that they are represented by vector fluxes at right angles to each other, and also to

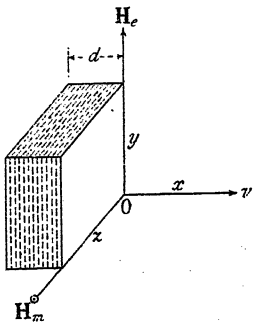


FIG. 3.

the direction of the fixed velocity v. These fluxes must bear a constant ratio to each other

$$\frac{\mathbf{B}_e}{\sqrt{e}} = \frac{\mathbf{B}_m}{\sqrt{m}} \qquad \mathbf{H}_e\sqrt{e} = \mathbf{H}_m\sqrt{m}$$

These are the ordinary properties of a ray of light.

For our present purpose the above laws yield another conclusion which is of more immediate use. We are assuming that the disturbance moves as a whole, along the axis of x, with a velocity v. Consider a rectangular block of it with edges each parallel to one of the axes. Let d be the depth of the block along the axis of x, and let the sectional area perpendicular to x be unity. Let $\mathbf{H}_e$ be along the axis of y, and $\mathbf{H}_m$ be along the axis of z. The positive direction of z is upwards from the paper as indicated by Silvanus Thompson's symbol ⊙. Consider the flow of energy, in the path of the advancing pulse, at some point O. This is zero until the pulse reaches O, it has some value $\mathbf{P}$ per unit cross-section while the pulse passes O, and is zero again after the passing of the pulse. The time taken for the pulse to pass in d/v. The total energy which passes per unit of cross-section must be equal to that contained in the block of volume d, or

$$P\frac{d}{v} = (\tfrac{1}{2}H_eB_e + \tfrac{1}{2}H_mB_m)\,d = \frac{H_eH_m}{v}d$$

Thus P is numerically equal to, and is given in vector form by,

$$\mathbf{P} = [\mathbf{H}_e\mathbf{H}_m]$$

Now this is the Poynting flux, discovered and proved by Poynting in 1884, and constituting the greatest contribution to electromagnetic theory since the death of Maxwell. The above argument does not prove the Poynting flux since we have made an assumption, but from our present point of view the important thing to note is that the value established by Poynting for this energy flux is exactly what is required to justify the assumption made, that an electromagnetic pulse with equal electric and magnetic energies per unit volume, and represented by fluxes at right angles to each other, moves forward at a fixed speed v perpendicular to each flux, carrying all its energy with it, and thus *leaving no energy behind it*. This means that no disturbance can be left in its track, since such a disturbance would need energy, and there is no source of such energy.

This explains the fact, always assumed about light, that a wave of light passes from a star to the earth without changing its character on the journey. Each ordinate of the wave represents a thin pulse of light which travels unchanged without affecting, or being affected by, any pulse which precedes it, follows it, travels with it, or crosses its path.

Heaviside's problem of high-speed telegraphy, including the more complex case of telephony, was that of finding the conditions to be fulfilled by the transmitting line, and by the receiving apparatus, in order that a pulse of potential, applied at one end of the line, would, in spite of the interference of matter, pass along the line, like the pulse in a ray of light, without leaving a trace of energy behind it to interfere with any succeeding pulse.

A large part of Heaviside's work was devoted to the study of reflected waves, but his whole object was to find out how to avoid them. The limit of the working speed of telegraphy is fixed by the fact that the reflected waves distort the signals and mix them up. He showed how to design the transmitting line and the terminal apparatus so that, in essence, reflections could be prevented. "It is possible to absorb completely an arbitrary wave by means of a suitable terminal resistance. Then there are no reflected waves."* When a circuit fulfilled the requisite conditions he called it "distortionless." His discovery of these conditions, and his recognition of the fact that they could be approximately secured in practice, shows that he had not only a scientific, but also a thorough engineering, grip of the cable problem.

His theory of the distortionless circuit dates from not later than June 1887,† but it would be quite a mistake to suppose that he relied on any one method for establishing the necessary conditions. His operator process was only one of these methods. He tried many ways, and was untiring in working out in detail a host of examples in order to prove that he got consistent results. Some one described genius as the power of taking infinite pains. It is usually a power which a genius displays less than any other. In Heaviside's case we have a strong combination of genius and industry. He did not establish his theory by any single demonstration, but as the result of the study, not only mathematically

* "Electromagnetic Theory," vol. 2, p. 74.
† "Electrical Papers," vol. 2, pp. 119–168.

but also physically, of an endless number of worked-out cases. It is this fact which makes it difficult to give any simple account of his work.

That, among other ways, he did regard his cable problem as comparable with that of a pulse of light can be shown by quotations from his writings.* In reference to a pure plane wave which "just goes on," he says: "To what extent this will continue depends upon the relation the constants of the circuit bear to the distortionless state. When the latter obtains, the wave is transmitted *without spreading out behind*, so that at a time t the initial state, if existent over a unit length, will be found over unit length at a distance vt to the right" but attenuated. "In all other cases there is reflection in transit, and the reflected portions travel back, besides getting mixed up together, thus making a tail." "The distortionless state forms a simple and natural boundary between two diverse kinds of propagation of a complicated nature, in each of which there is continuous distortion which is ultimately unlimited." "When a circuit has been brought to this (distortionless) state, then arbitrary signals of any size and manner of variation, originated at the beginning of the circuit, will run along it at the speed of light, and in doing so suffer no alteration save a weakening . . . the succession of values will faithfully repeat those at the origin."

(4). Reflected Waves.

Heaviside, in more than one place in his book, points out that the series and shunt resistances of the transmitting line absorb energy from the advancing wave; that each resistance reduces the electric and magnetic energies but in different proportions; and that unless certain relations hold between the various inductance and resistance constants of the line, some of the Faraday tubes will be reversed. This leads to reflected waves.

In a wave pulse, the values of B_e and B_m represent equal energies per unit volume, and thus bear a fixed ratio to each other, so that by adopting suitable units we can use the same number $(a + b)$ to denote each of them. The square of this number in terms of another unit will represent the total energy per unit volume. The value of P, the Poynting flux of energy per unit area, is proportional to the product B_eB_m, so that this product with due regard to sign, will denote P in terms of yet another unit. If now, owing to the action of matter upon the incident pulse, the electric flux $(a + b)$ is partially reversed so as to become $(a - b)$, we get two pulses, one transmitted and the other reflected, as follows:—

	B_e	B_m	Energy	P
Incident pulse	$a + b$	$a + b$	$(a + b)^2$	$(a + b)_2$
Transmitted pulse	$+ a$	$+ a$	a^2	$+ a^2$
Reflected pulse	$- b$	$+ b$	b^2	$- b^2$

The total energy is reduced from $(a + b)^2$ to $a^2 + b^2$, the loss $2ab$ being absorbed in the resistances. One pulse goes forward with energy a^2, and the other backward with energy b^2. Although this is only an illustration, it appears to represent what happens.

The line resistances must reduce the energy of the advancing pulse, but it does not follow that the pulse must split up. The condition that the pulse fluxes move together is that their energies must remain equal to each other, not that they must continue constant in time. Even in a light wave the energies continuously diminish, because, as the wave spreads spherically, the pulse energies are distributed over an ever-increasing area of wave front, so that the energy per unit volume diminishes. The important point is that, though this is the case, the electric and magnetic energies per unit volume diminish in the same proportion, and since they start equal they always remain equal.

The absorption of energy in the resistances causes not one effect but three. Two of these are direct and of no importance. The third is indirect and is all important. The loss of energy must weaken the signal. This is of no consequence since all that is needed is a more sensitive receiver, and electrical apparatus never fails from want of sensitiveness. The heating of the wire gives rise to heat waves. Each electron in the wire insists on blowing its own trumpet. There results a concert of a kind involving "harmony not understood," but it has no connection with the signal and does not affect it in any way. If, however, the energy absorbed in the resistances is withdrawn unequally from the electric and magnetic energies in the pulse these two energies are no longer equal, the equality of the velocities, $v_e = v_m$, no longer holds, and the pulse must break up into parts. Each of these carries the signal with it. The strength of each part must be proportional to that of the original pulse. The signal is represented by the modulation, or law of variation, of the strength of the pulses in the sequence forming the wave, so that each part represents a sequence having the signal imprinted on it. One part represents a forward wave which proceeds towards the receiver, the other represents a wave which goes back. If it always went back it would not matter, since it would never reach the receiver; but, unfortunately, the reflected wave meets another conducting surface, is reflected a second time, and goes forward again, reaching the receiver as an echo at a time subsequent to the forward wave. It thus arrives with another part of the signal so that confusion results at the receiver.

What happens in an ordinary telegraphic line is illustrated in Fig. 4. Suppose that a pulse of potential, impressed on the line by pressing a key, represents a dot signal d_0 travelling along the line at the speed of light in the direction of the arrow, from a transmitting station T to a receiving station R at a distance of 500 km, represented by 0·5 on the diagram. This pulse will splash against R. Its energy will be in part absorbed, but some of it will take the form of a reflected wave which will return to T, where it will give rise to another reflection, which will follow d_0 as an echo d, after a time corresponding with twice the distance between the two stations, or 1 000 km. The echo d_1 will behave exactly like d_0 and hence there will arise a succession of echoes d_2, d_3, etc. These echoes are shown in the figure to the right of d_0 spaced at distances 1 000 km from each other. Of course nothing exists to the right of T. The pulses d_1, d_2, etc., are but shadows forecasting coming events. The event does not exist until the moment the shadow arrives at T, after which it goes on as a real echo and is received as such at R. The effect at R is, however,

* "Electromagnetic Theory," vol. 1, pp. 408–410.

exactly as if d_1, d_2, etc., were real pulses following each other in procession, all at the speed of light and spaced as indicated. In theory the number of these echoes is unlimited, so that some of them come on with, and others actually behind, a dash signal D impressed on the line by the operator at some time interval after the dot signal d_0. The effect is to spread out the dot signal. For the moment we are ignoring attenuation, and we assume that the line itself is perfect, so that reflections only occur at T and at R.

If, for the dot signal, the key is pressed for only 0·0001 second, during which time light travels 30 km, the depth of the d_0 signal will be 30 km, or much less than 1 000 km, the spacing of the echoes, hence all these "d" signals will be separate. If, however, the key is pressed for 0·01 second the depth of each pulse will be 3 000 km, so that the pulses will overlap. Moreover, the line is not perfect, so that reflections arise at every point of the

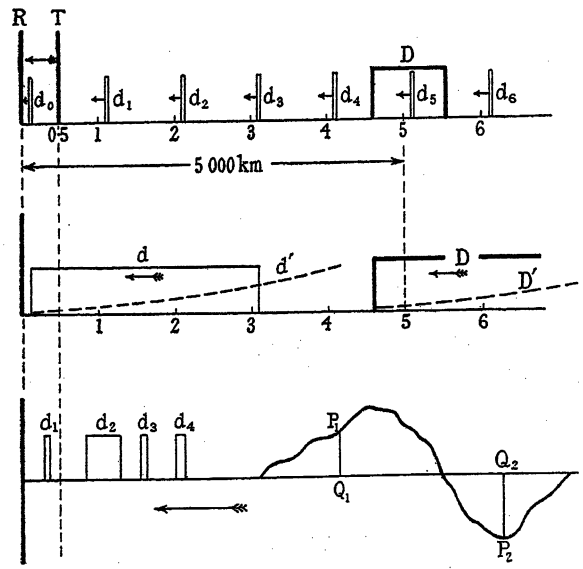


FIG. 4.

path. The result is that, as indicated in the middle diagram, the received signal d′ will not be represented by the rectangle d denoting the signal sent, but by a curve, the ordinate of which, while greatly attenuated at the start, will rise continuously owing to the cumulative effect of successive reflections, and will be spread over a base much greater than 3 000 km, the original depth of the pulse. In theory it will be indefinitely prolonged, and in practice if the dash signal D is made after too short a time interval, the corresponding D′ signal as received, which will also be greatly attenuated at first, will have its early portion overwhelmed by the rear part of the d′ pulse, so that dots and dashes will get hopelessly mixed. If, however, we can prevent the occurrence of reflections, it does not matter how complicated the signal may be. We can assume that it is represented, as in the bottom figure, by an isolated, irregular set of signals d_1, d_2, etc., or by a continuous wave such as P_1P_2 denoting a complex telephonic message. Each ordinate PQ of the wave can be regarded as an independent pulse travelling along the line without interfering with its neighbours, and without leaving behind it any trace of its passage. Attenuation there may be, but it will be the same for each ordinate. The whole wave will go through, keeping its wave-form intact. It only needs a good receiver to interpret the signals perfectly, however rapid and however complex they may be.

Heaviside saw all this clearly before the time of Marconi and before even the earliest experiments of Hertz and Lodge. It is explained in the descriptive parts of his writings, which are devoid of analytical argument. He does not connect up with the equations as I have tried to do. But it is certain that he did this for himself, and that in doing so he used the standard physics of Maxwell's theory, and the standard mathematics natural to it. He did not for this purpose use his operator method at all. This method was not evolved until after he had seen from physics that, in order to make the transmitting line suitable for high-speed signalling certain realizable conditions had to be met. He used the operator method merely to find out these conditions. To do this, he applied main force. The method was an experimental one and needed a thorough mathematical investigation in order to justify it. The conventional mathematician takes much interest in a pure mathematical research, but Heaviside was not a conventional mathematician. He always needed an objective, and, as soon as he saw how to reach it, he went straight for it without troubling more about theory. He was like an engineer who has to reach a result within a strictly limited time, and who has to force the pace and proceed by trial and test, without spending much time on theory.

Before leaving the subject of reflections, reference must be made to the Heaviside layer, since no account of Heaviside's work would be complete without it. The theory of this layer forms one of the most important contributions to the theory of radio-telegraphy. It was Heaviside's recognized position as an authority on Maxwell's theory that drew public attention to the possibilities of this layer, and caused experiments on it to be made as soon as suitable instrumental methods became available. It is well understood now that reflections from the layer enable the waves to keep to the curved surface of the earth. It is found possible to detect these waves after travelling not only a quarter way, or half way, round the earth, but also after travelling once, twice, and even four times completely round the globe.

Prof. E. V. Appleton, whose experimental work on the Heaviside layer is of great interest and importance, has been good enough to help me to illustrate these matters in Figs. 5, 6, and 7. The first two are reproductions of the actual record of receiving apparatus, while the curves shown in Fig. 7 have ordinates representing measured values. Fig. 5 represents round-the-world echoes received on a travelling photographic plate, the time intervals being measured in the ordinary chronographic manner. The emitted signal is double, and the corresponding echoes are distinguished by Roman and Arabic numbers. Each echo arrives about one-seventh of a second after its predecessor, this being the time taken by radiation at the speed of light to go round the earth

by the polygonal path due to successive reflections at the Heaviside layer. Three round-the-world echoes are shown. Fig. 6 represents two signals a, a', received at a German station, from a transmitting station in America. One signal arrives by the shorter route over the Atlantic, and the other by the longer route over the Pacific. In this case the time interval between the two signals is less than one-seventh of a second. The experiments of Figs. 5 and 6 are due to Quäck. The tests shown in Fig. 7 were made by Prof. Appleton, and represent the

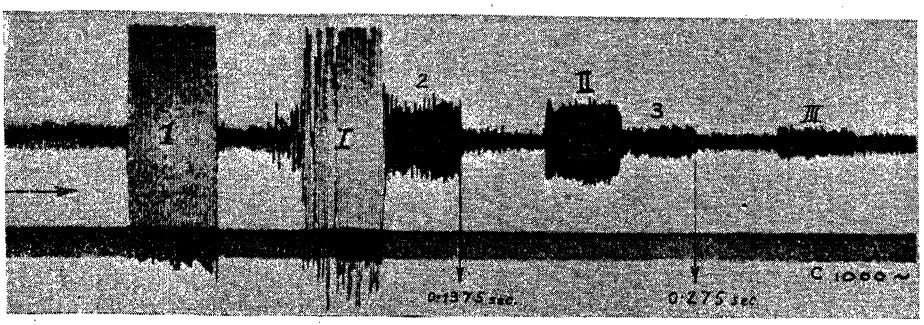


FIG. 5.

record made at King's College of reflections at the Heaviside layer caused by directing a beam of radio waves nearly vertically upwards at the East London College a few miles distant. The waves are reflected in succession at the surface of the layer and at that of the earth, the number of reflections occurring between the two stations being dependent on the original inclination of the particular ray. The figure shows five such

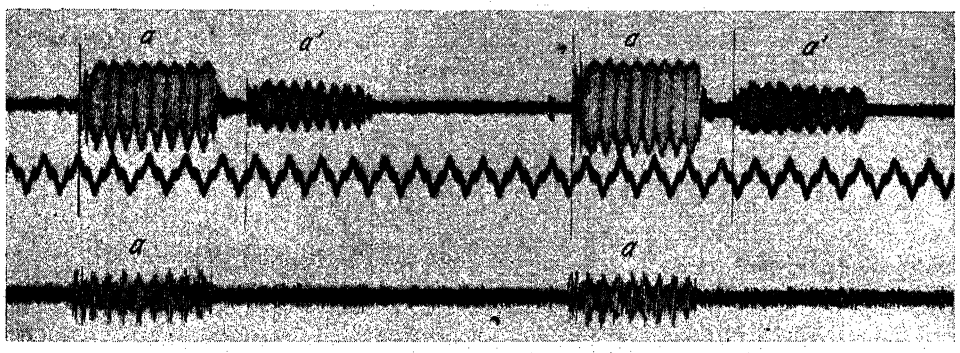


FIG. 6.

echoes, F_1 to F_5, besides the direct ground signal G, which arrives first but which is weak in comparison, since the transmitting beam is directed upwards so that its rays are much weaker in the horizontal than in the vertical direction.

Such experiments are all subsequent to Heaviside and we cannot dwell on many points of interest set forth in the original papers.* They are, however, quite to the point, since they prove the existence of the Heaviside layer, and the action of this layer in producing reflections.

(5). THE CABLE PROBLEM AND THE OPERATOR METHOD.

Heaviside realized that what he had to consider was not the behaviour of a complex wave, but that of a single pulse. This pulse is a solitary wave advancing over a dead smooth sea. Heaviside wanted a form of mathematics which would enable him to ride on the front of this wave and to study what happened to it when it met obstacles. In the ether ocean these obstacles are not like rocky islands, or iron-bound coasts. They are much more like floating ships, or floating masses of seaweed. He had to find the conditions under which no reflected waves would occur. It will be found that, though much of Heaviside's mathematics deals with waves, his sole point of interest is what is happening at the wave front. He pays no attention to the rest of the wave. He merely wants to know what happens to a thin pulse.

It was not for want of searching that Heaviside quite failed to find in mathematical work any form of analysis suitable for his purpose. Those who have implied that what he did with his operators can be done by other and better methods, cannot have understood what the problem really was. There are several methods for dealing with the steady or periodic state, and also for

* For the work of Quäck, see *Jahrbuch der drahtlosen Telegraphie*, 1926, vol. 28, p. 177, and 1927, vol. 30, p. 42. The subject is dealt with by Appleton in a lecture on "Wireless Echoes" before the British Association, 1930, and also in "Wireless Echoes of Short Delay," *Proceedings of the Physical Society of London*, 1932, vol. 44, p. 76. Appleton and Barnett first proved the existence of the Heaviside layer at a height of 90–100 km, using broadcasting wavelengths (*Proceedings of the Royal Society*, A, 1925, vol. 109, p. 621). Appleton also was the first to find the second or upper layer in 1927 (*Nature*, 1927, vol. 120, p. 330). This upper layer is reached by short-wave radiation after penetrating the lower layer. The tests on Figs. 5, 6, and 7 were all made on the upper layer.

dealing with the building up of such a state by transients represented by exponential changes or undulating surges. Heaviside's operator method can be applied to these,* and, as a matter of fact, in technical publications it has been more used to deal with such states than for Heaviside's main purpose. Heaviside was not in the least interested in either of these states, but in an initial state which preceded both. The mathematician, when dealing with a problem involving distributed capacitance and inductance, divides up the circuit into elements, and uses differential equations in connection with them. But, however small the condenser element may be, it is assumed that the distribution of Faraday tubes connecting the plates is just as if the voltage between them were steady, and as if the tubes extended throughout space. The same assumption is made with regard to the inductances. These assumptions are quite wrong at the start, since a disturbance can only spread at a limited speed v, so that at a time t it must always be confined within a sphere of radius vt. Heaviside was interested only in the front of the advancing disturbance. The transient state represents the building up of the final

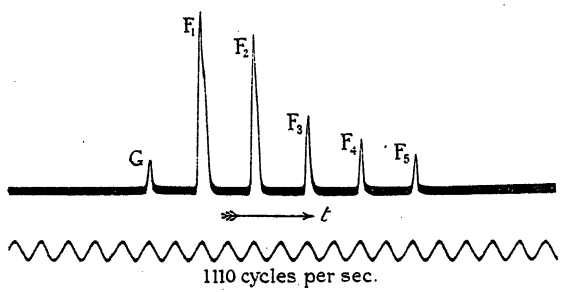


FIG. 7.

state by means of the cumulative effects of a multitude of reflections which are successive, not simultaneous. Heaviside wanted to study the behaviour of the first pulse which travels beyond the reach of even the first reflection. Mathematics contains much about waves. Hertz gave some beautiful examples in one of his papers. Such work either is confined to ether free from matter, or deals with forms of matter so simple mathematically that they do not at all resemble a telegraphic circuit. Heaviside wanted to reach a definite result in an actual engineering problem. He was not the man to replace the physics by a convenient assumption in order to revel in pure mathematics. Instead of discarding the physics, he threw away the mathematics and stuck to his problem. Finding no mathematics to help him, he went ahead without it.

The problem being to find out what happened to a pulse, Heaviside had to do two things. He first had to express a pulse in mathematical language; he next had to deal with the pulse. For the first purpose he used his unit function, and, for the second, his operator method. The two are quite distinct, but since each is used in the same example, while neither is explained, it often seems to be assumed that they are essential parts of one method. They form two incomprehensibles, and

* The result in such cases is simply to establish the ordinary alternate-current formulæ involving impedances, or complex numbers. Heaviside had done all this in 1878 by Boole's method, in his early telephonic papers, before alternate currents had come into commercial use.

the presence of the one is held to account for the mystery of the other. They are quite separate things, one being wanted to formulate the problem, and the other to solve it. Heaviside deals with each of them in a way which shows up his resource and also his attitude towards mathematics. He was more interested in the use of mathematics than in the making of it. He showed this in his work on the cable problem, just as Fourier did in his work on the theory of heat. The work of each has been regarded by the rigid mathematician as sadly lacking in the rigour now "required" by such mathematicians.

Heaviside held that the most convincing of all proofs of a method was the verification of results predicted by it; that there were ways other than mathematical ones for proving things; and that sometimes these other ways could even be used within purely mathematical regions. In particular, since mathematics can often be used to deduce, from known physical results, other results not yet established, it must at times be possible to use the physics of two sets of known results to prove the strength of a mathematical chain connecting them. He frequently uses physical arguments to establish mathematical results. "Familiarity with the working

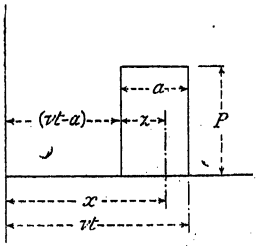


FIG. 8.

out of physical problems breeds contempt for the idea of requiring a special demonstration of what seems to be necessary." He even says: "Physics is above mathematics, and the slave must be trained to work to suit the master's convenience." Heaviside has never been popular with mathematicians.

It is easy to represent by a curve a pulse having strength P for certain values of the variable z, and having zero strength for all other values of z; but it is not easy to find a mathematical formula for it.

Heaviside assumed the existence of a unit function $H(z)$ which was to be unity whenever z was positive, and zero whenever z was negative. A stationary pulse of strength P, and base a, can then be expressed as

$$P\big[H(z) - H(z - a)\big]$$

since outside the range $0<z<a$ the two values of H are either both zero or both unity, so that their difference is zero and the quantity vanishes; while within this range one of the values of H becomes unity and the other zero, so that the expression gives the true value P of the pulse.

If the pulse is moving with velocity v, it will be seen from Fig. 8 that we have at any time t

$$z = x - (vt - a)$$

and by substitution we see that

$$P\big[H(x - vt + a) - H(x - vt)\big]$$

represents the true value of the pulse, whatever values we give either to x or to t.

This unit function is used by Heaviside throughout his work. He argued from physical considerations that such a function must exist. He did not know, and did not even try to find out, what it was. He could see that it must have certain simple properties, and that he could use it. This was quite enough for Heaviside. His argument in what he calls " physical mathematics " can be illustrated with the aid of the example already referred to.

Let a switch close at time 0 a circuit governed by

$$E = RC + L\dot{C}$$

with $E = 20$ volts, $R = 5$ ohms, and $L = 5$ mh. The mathematician gives us the solution as

$$C = \frac{E}{R}(1 - e^{-Rt/L}) = 4(1 - e^{-1\,000t})$$

This tells us that C reaches its steady value of 4 amperes in a small fraction of a second. It also tells us that at a time of -1 second it was (approximately) -8×10^{434} amperes. Heaviside talks darkly of men who strain hard over a few gnats yet " swallow, quite unawares, *all* the camels in Arabia." Yet what is the act of swallowing a few camels compared with that of swallowing a negative current such as this? Common sense may point out that the switch was not closed at the moment in question. This may be common sense. Is it mathematics? The switch is an important part of the circuit but forms no part of the mathematical problem. The precise mathematician, who declares that mathematics is nothing if not accurate, has given us an answer which is not even approximately correct. He says blandly that t is restricted to positive values. But who has so restricted t, and where does the restriction appear in the mathematics? The fact is that E is not 20 volts, but 20 $H(t)$ volts, or alternatively that R is 5 ohms divided by $H(t)$. The factor $H(t)$ appears in the answer for C, as well as in the original equation. This is the mathematical reason why C is zero until t is positive.

This example can now be used to express in full form the operator problem, which we see involves not only the operator but also the special function $H(t)$. We have

$$C = \frac{1}{R + Lp} E \,.\, H(t)$$

This is only a simple case. Let us consider what it means mathematically. The $H(t)$ function, which Heaviside did not even try to formulate, can be shown to be an infinite series of a most complicated kind. The pulse E, to which the operator is applied, may in simple cases be a constant, but in general it changes in an arbitrary fashion over a range of the variable, so that it has to be represented by a Fourier series also containing an infinite number of terms. The operator itself, whether simple or complicated, is always expanded by Heaviside into an infinite series of terms involving powers of p. Heaviside did not know, and did not try to find out, what p was. He merely knew how to use it. We have thus to deal with the product of three infinite eries.

A mathematician will discuss at length the convergency or divergency of an infinite series, and at even greater length will point out the grave risks attending any attempt to multiply together two such series. His views about the multiplication of three series, like these of Heaviside, do not seem to have been published. There may be limits to what a publisher can print.

Heaviside's view of the problem was not that of a mathematician but that of an engineer. His problem, however formidable in appearance, is, after all, much like that which the ordinary engineer has to face every day in his life. Consider how an engineer deals with a substance like steel. Any good modern book on physics will convince you that it is appalling to contemplate the multitudinous things about the structure of steel which the engineer does *not* know. What should give rise to no little surprise is that, in spite of such a terrible curse, not one of them seems a penny the worse. The engineer does not, to begin with, try to find out all about steel. He simply uses steel. He tests it, finds out some of its properties, learns from experience that he can rely on those properties, designs his engines and structures accordingly, and gets results quite satisfactory, not only to himself but to the world at large. No one is so sure as the engineer that, if a steel will stand a pull of 10 tons to the square inch, it will go on standing that pull in spite of all the structural theories depending on groupings of molecules, or of atoms, or of electrons, or of any of the other " ons " by means of which modern physics explains, or explains away, the structure of steel.

Heaviside's motto was "first get on in any way possible, leave the logic for later work." He got down to his problem and said to himself something to this effect:—I have now reached at last an exact mathematical representation of my problem . . . well . . . if this is a precise expression of the problem to be solved, it must in some way be an equally precise statement of the answer to be found. There is no need to worry any longer over mathematics. I have simply to read off the answer.

He tried in all sorts of ways to do this. The marvel is that he got through. He no doubt had failures, and no doubt used these as steps to success. He soon found out how to intepret his operator p so that in some cases, in which the solutions were already known, he got the right results. He thus arrived at his " rule " by use of which he could get a definite result in every case. These results proved to be consistent in connection with similar problems, or with the same problem in various forms. Heaviside knew well, and admitted fully, that such results were not proved. No one troubled less about proofs, but no one troubled so much about verification. He proved nothing. He simply made sure he was right. With Heaviside a proof was in general little more than a way of meeting the whims and fancies of other people. To make sure of being right is to appeal to experience for a judgment. This test Heaviside never failed to apply in ample fashion.

Now we all use experience, but theorists are apt to forget that on all questions experience is the final court of appeal. The engineer makes good use of matter without knowing what it is. He reproduces results, and forms his own theory about the process. There never

was a greater mistake than to suppose that the practical man looks down on theory. No one thinks so highly of it. He only makes one condition. The theory must be his own. In this respect the engineer is sadly like men who are not engineers. The theory may be crude, yet it is founded on experience, and, within the range of that experience, it is reliable. That is enough for the engineer.

Next take the physicist. No one evolves such weird theories about matter. They make one ask:—Why do these imaginations rage so furiously together? Yet, however wild the theory, if it leads to experiments yielding consistent results, and if these results serve to connect facts not previously associated together, the physicist is quite sure that he has made an advance, and that his theory contains some of the truth. No theory can contain the truth, the whole truth, and nothing but the truth.

Finally, take the mathematician. What does the mathematical leader do when he is in difficult case? He evolves what he calls a symbolical method. He does not explain, or even define it. He is not quite sure of his ground, but he sees a possibility of advance. In essence he proceeds just as Heaviside did, though he is rarely so frank about it. He does not understand his method, but goes ahead as if he did, and tests his results for consistency. Now consistency of results is to the mathematician what experimental tests are to the physicist and what experience is to the engineer. It is the mode of testing the range within which the method can be trusted to give reliable results. In no case is a full proof given.

If there is any difference between the unrecognized method of Heaviside and what is one of the standard methods of the pure mathematician, it is due to a fact characteristic of Heaviside. In his case there was always a definite object in view. From this he never turned aside to evolve interesting mathematical theorems. He worked steadily on at his actual problem until he carried it through to a finish. The formula was not the finish, as is usually the case. With Heaviside the formula was but the beginning, not the end, of the solution. He went to great labour with arithmetic to grip the meaning of his formula, and used every physical argument he could think of to realize its application. His solution was reached more by physics than by mathematics. The most extraordinary fact about the operator method is that it is an abstruse form of analysis which might have been expected to attract the mathematician and to repel the technical man, yet it is to technical publications one must turn for appreciation of Heaviside's work. This work aimed at useful results, and it is these that appeal to the engineer. It was the useful trend of the work that deflected from it the attention not only of the mathematician but even of the physicist. The physicist did not realize that, technical as it was, the problem was in the main one in pure physics, and the mathematician did not see until quite recently that the analysis in spite of its usefulness was yet a form of mathematics of singularly pure type. Since Heaviside did not profess to explain his method, it would be out of place in an account of his work to dwell upon what he did not do; but it would not be right to make no reference whatever to the large amount of mathematical work which has been done in making clear the actual working of the method and in searching for a firm base on which to justify it.

The late Prof. Bromwich was the first mathematician of high standing to show sympathy with the operator method. His earliest paper was published in 1916. Since Heaviside's death in 1925 other efforts at explanation have been made, and several good books dealing with the method have appeared in print. These books explain in a simple way the actual working of the method in connection with examples such as Heaviside used, and also in regard to what may be called more up-to-date examples in telegraphy. Whether any fundamental theory of the method is given is, however, quite another matter.

The two most original contributions to this subject appear to be those of Prof. Bromwich and of J. R. Carson. Bromwich's method is one of great beauty and power. It justifies and extends Heaviside's results. Nevertheless, I cannot imagine two methods more unlike than those of Bromwich and of Heaviside. The Carson method, on the other hand, is very similar in form to that of Heaviside. It approaches the subject from quite an independent starting point, and, by basing the analysis on what is known as an integral equation it puts to new use a large number of established mathematical results in a way such as greatly to extend the application of the method. Moreover, Carson applies Borel's theorem. By so doing he extends the method still further and, what is even more important, he appears to give the method much additional power. This has been shown in the work of Carson himself, and still more in quite recent work by Balth van der Pol.

In my own contribution to the subject the aim has been to formulate the unit function in precise mathematical language, and also to establish theorems justifying the use of Heaviside's index operator p. In my view, the connection between the methods of Heaviside, Bromwich, and Carson, is simply this. Each is a symbolical method. Every symbolical method proceeds on assumption, since there must be an assumption about any method which involves taking a step that is not fully explained and justified. Each method starts from a different base, but the actual working is not questionable in any case; the results reached in each case are the same, and are also known to be correct. The natural conclusion is that there is something common to the assumptions made in the three cases, and that this common part must be true. I have explained my views of this elsewhere, but, whatever the truth may be, the great interest of Heaviside's work does not lie in any theoretical justification of it which has been, or which may be, given, but in the fact that Heaviside got through without any explanation at all. He evolved a working method based upon trial, confirmed on test, and finally put to use on the largest scale humanly possible.

Conclusion.

Heaviside's work can be summarized in four conclusions, three of which are not likely to be disputed, while the fourth is, from its nature, very debatable and will certainly not be generally admitted.

In the first place, Heaviside's actual analysis was always simple, clear, direct, and compact. His writings do not exhibit the orderly arrangement of a textbook. It was his characteristic never to leave a definite problem unfinished; but when engaged on pure theory he could hardly get through a page without wandering off into some application to physics involving more or less debatable assumptions about matter. He never troubled to assemble his results. He uses his operator throughout his work, but does not trouble to give anywhere a complete definition of it. He puts the electromagnetic laws into the simplest and most symmetrical of forms, but nowhere collects them into four lines, as can readily be done. He was not writing a textbook for beginners, and certainly he was not writing a so-called elementary treatise for those who love rigour. He was dealing with electrical problems in a series of articles published in the *Electrician*, a weekly technical journal. The articles were spread over a period of many years. He was allowed great freedom as to what he wrote, but one condition was always strictly imposed. After first publication not a letter could be changed, since the type was kept set up until the corresponding section of the book was printed. Whose writings would survive so well as those of Heaviside a test so severe and so prolonged? These writings are often called obscure. This is true in two important respects. His efforts to make things clear seemed to stop with himself, for he never seemed to imagine that a point clear to himself could be other than clear to his reader. He would at times stride casually over a mountain and leave his reader to struggle after him to reach a ridge from which he could be seen in the distance. The basis of his operator method has been obscure to everyone, but Heaviside himself did not profess to understand this. He merely showed how to work the method, and claimed that it led to correct results. In all cases he was obscure only when he himself thought there was no need further to explain.

Next, as regards the electromagnetic theory, Heaviside's work was to simplify its basis and to develop a mathematical machine specially suitable for use with it, and this machine he applied to physical problems in a way that aroused the admiration of the leaders of electrical science. No greater service can be rendered to any theory than to put its fundamental points in the clearest and most workable form. The greater the theory the greater is the service. This function Heaviside fulfilled so well that he has fixed his mark on Maxwell's theory.

Thirdly, his work on the cable problem, while all directed to one end, necessarily had to surmount one difficulty after another and did a great deal more than lead to the theory of the loading coil. It shows that ordinary telegraphy is but a special form of directed wave telegraphy, and that Heaviside was the first radio telegraphist. The wonderful work of radio engineers refers to the invention and development of the transmitter and of the receiver. In regard to what happens between the two there is more to be found in the writings of Heaviside than elsewhere. Heaviside's analysis in connection with Maxwell's theory, though involving many short cuts, was yet all of standard type, and showed that he could use standard mathematical methods as well as anyone. In the analysis of the cable problem, all things "suffer a 'sea' change into something rich and strange." He threw over conventional forms of mathematics, but never left his problem. The reader could always get help from good textbooks in regard to any difficulty met with in understanding the work on Maxwell's theory, but as regards the cable problem no mathematical library included, until quite recently, any book which is at all helpful in connection with the operator method. Heaviside was a rough-rider exploring new country, not a maker or mere user of railway lines. His work is not to be judged by the difficulty of following in his tracks, but by the news he brought home with him on his return.

We come finally to the debatable conclusion. If mathematicians ever spend on the work of Heaviside as much as 1 per cent of the time they have spent on the work of Fourier, they will find many things which will astonish them. They may not be willing to admit—what I suggest is the fact—that Heaviside was a second Fourier. This much at least is certain. Heaviside, in his search for a solution of a definite problem, explored new ground and turned up many by-products to which he paid no attention, though at times he made a passing comment on their mathematical interest. The result is that his writings are sprinkled with what may be called diamonds in the rough. The mathematician does not appreciate diamonds until they are thoroughly worked up and until they sparkle from every point of view. Many years may pass before these by-products are examined and fitted for admission to the mathematical museum, but sooner or later this work will be done. It will then be clear that the reputation of Heaviside, great as it now is, will become yet greater as time goes on.

APPENDIX 1.

Historical Notes.

An immense advance, both in electrical engineering and in electromagnetic theory, took place during the six years 1882 to 1888. Electrical developments were brought to public notice by the Crystal Palace Exhibition of 1882. This date marks the coming of the good armature due to Gramme, and of the glow lamp due to Edison and Swan. The construction of good dynamos dates from 1886, when two important papers were published dealing with the magnetic circuit. One of these was due to Hopkinson, and the other to Kapp. The former was highly scientific and quite to the point, but not widely understood. The latter contained Kapp's idea of magnetic resistance, now called reluctance, which made the application of known theory crystal clear to the designers of dynamos. The year 1888 marks the coming of alternating-current practice, the date of the Grosvenor Gallery installation, of the running in parallel of transformers and of alternators, and of the generation and distribution of high-tension currents by paper-insulated cables; all developments largely due to the genius of Ferranti.

Maxwell's theory dates from 1864, and his book on "Electricity" from 1873 (first edition), and from 1881

(second edition). It was in 1882 that Heaviside began to write papers on telegraphy from the point of view of the wave theory. That year is important for another reason. Prof. G. F. Fitzgerald tried very hard to devise experiments to prove the existence of Maxwell's waves. He did not succeed, but he did suggest the method afterwards used by Hertz for producing short waves, since he pointed out in 1882 that the discharge of condensers of small capacitance through coils of small inductance, would yield the short waves required. It only needed a spark to convert the suggestion of Fitzgerald into the experiments of Hertz. No one thought of using a spark as an indicator of voltage. Hertz did this in 1886, but his early papers were not printed in Germany until 1887, and his work was not known in England until after Lodge, using sparks imitating lightning flashes, had obtained results similar to those of Hertz. The waves were studied by Hertz as from a ship at sea, and by Lodge as they broke upon the shore. The experiments of Hertz resembled those of light or sound, while those of Lodge formed the earliest examples of wireless telegraphy. Hertz's work was not widely known until Fitzgerald drew public attention to it in an address to the British Association in 1888.

The year 1888 not only marks the beginning of alternating-current engineering. It is as good a date as can be chosen to denote the start of the supremely important researches of J. J. Thomson on the conduction of electricity through gases, which led to the discovery of the electron and to the revolutionary changes in physics. The new theories made possible the invention and development of the heavy-duty mercury-arc rectifier, and also of the thermionic valve by means of which broadcast telephony has been made possible.

Heaviside's share in this development is represented by many papers, written between 1882 and 1885, which made clear, and developed, Maxwell's theory. Poynting and Heaviside were working on this subject quite independently between 1883 and 1885. They covered much the same ground, and ran a close race ending in a dead heat.

In 1883 Heaviside developed some early work of Maxwell on the inductance and resistance of solid conductors and cores for transient currents. He was dealing with what is now known as the skin effect in thick conductors. Lord Rayleigh was doing similar work, and both he and Heaviside were aware that the results, in the light of Maxwell's theory, showed that rapidly changing currents behaved as if they entered, or left, the core through the dielectric, rather than by way of the circuit. The results were as yet devoid of experimental evidence, and few took interest in these investigations. In 1886 the President of this Institution was Prof. Hughes, the inventor of the printing telegraph and also of the microphone. In January of that year he delivered his presidential address, during which he showed and described some wonderful experiments with his induction balance. The effects were most complex, and were due to a combination of many causes. They aroused much attention and criticism. No one was better able to criticize them than Heaviside, who had made a profound study of the induction conditions needed for a true balance. He did criticize Hughes's results, but he was also keenly interested in them, because he realized, and was the first to point out, that they involved the first direct experimental evidence* in favour of Maxwell's wave theory. They preceded the earliest experiments of Hertz.

Heaviside was aware in 1883 that there was no foundation for the common idea that the energy of an electric current travelled round the circuit with the current, but he had not yet worked out from Maxwell's equations how the energy moved. In his "Electrical Papers," vol. 1, p. 377, in a chapter entitled "Transmission of Energy into a Conducting Core," he writes "the direction of maximum transference is therefore perpendicular to the plane containing the directions of the magnetic force and of the current, and its amount proportional to the product of their strengths, and to the sine of the angle between their directions." This was published in the *Electrician* on the 21st June, 1884. He makes no mention of the work of Poynting, though, at a later date, he fully acknowledges Poynting's priority. It is possible, though hardly likely, that he had heard of Poynting's result, but he could not at this date have seen Poynting's paper, since this contains a footnote dated the 19th June, 1884 (see "Collected Papers," p. 184), and could not have been published at the time Heaviside wrote the article.

Poynting's paper containing the theory of the flux of energy, was sent to the Royal Society in December 1883, and was read in January 1884.

During 1884 Heaviside completed his work on Maxwell's equations, and succeeded in putting the fundamental laws into a simple symmetrical form. His results were published, together with his independent proof of the Poynting flux, in January 1885. In February 1885 Poynting read before the Royal Society a second paper which developed the results of the previous (1884) paper. It analyses Maxwell's theory, shows the significance of the cross-cutting law, 4 (c.c.), and, in general, expands his views about the physical nature of the electromagnetic fluxes. It is mainly in regard to the nature of these fluxes that writers on Maxwell's theory differ from one another. It is of special interest to contrast the views of Poynting with those of Heaviside, since each discarded from Maxwell's theory certain points which the other retained.

APPENDIX 2.

The Nature of the Fluxes in Maxwell's Theory.

Faraday's conception of fluxes was physical, while that of Maxwell was mathematical. The wave theory introduced two new scientific concepts: the principle of the localization of energy, and the concept of dielectric currents. Maxwell did not give any clear physical explanation of what he meant by a dielectric current, and, since a conduction current was assumed to flow

* It is evidence of the skin effect that is here referred to. Mr. Evershed in his summary last year of the work of Hughes (*Journal I.E.E.*, 1931, vol. 69, p. 1248) shows that "Hughes did in fact discover the coherer" and used it as a relay, with a telephone and battery, to detect wave effects at distances up to 300 yards. At the time these results were obtained they were regarded as ordinary inductive effects. In connection with early work on electric waves, reference should be made to the work in 1870 of Bezold who used dust figures, to detect nodes and internodes. Hertz paid a graceful tribute to this work by including a summary of it in his book on electric waves.

along the wire in the direction of H_e, the electric force, it was natural for most students to regard a dielectric current as a vector directed along H_e. This is not really in accordance with the views of Faraday, who always refers to transverse action. Poynting in his 1885 paper adopts a " change in the point of view " in which " induction is regarded as being propagated sideways rather than along the tubes or lines of induction." This amounted to a return to Faraday's physical conception of fluxes. Poynting turns the law 4(x) into the form 4(c.c.), but does not put it into the vector form 4(v).

Heaviside followed Maxwell in treating the fluxes as purely mathematical. It is curious that he does not appear at all to favour the concept of lines or tubes of force. He says (" Electromagnetic Theory," vol. 1, p. 30): " I must, however, wonder at the persistence with which the practicians have stuck to ' the lines,' as they usually term the flux in question." Poynting's concept of a current C was " that C electric induction tubes close in upon the wire per second." This concept of transverse action harmonizes with the vector law 4(v), a law which was in essence realized both by Heaviside and by Poynting, but which, for quite different reasons, neither of them used in analysis.

Heaviside maintained that Maxwell, when establishing his theory, cleared away many cobwebs from the older theories, but did not entirely remove them, since he retained in his equations certain needless quantities expressed in terms of potential functions involving the idea of action at a distance. Hertz agreed with this view, and discarded all remote action effects. In his work on " Electric Waves " (translation by Jones), he says (p. 195), in reference to Maxwell's representation, that " it frequently wavers between the conceptions which Maxwell found in existence, and those to which he arrived "; while as regards the work of Heaviside, he says (p. 196), " from Maxwell's equations he removes the same symbols as myself; and the simplest form which these equations thereby attain is essentially the same as that at which I arrive." Thus Heaviside and Hertz each regard the circuital laws 4(c) as both necessary and sufficient. They gave Heaviside all that he wanted, and this appears to be the chief reason that he made no use of the vector law 4(v). Poynting, however, clung to Maxwell's ideas. Though he arrived at both 4(c) and 4(v), he did not regard either of these laws as sufficient, and used Maxwell's original equations in a slightly modified form.

Heaviside did not pay as much attention as Poynting did to the physical nature of fluxes, but no writer on electromagnetic theory is so insistent on the necessity of regarding H_e, B_e, H_m, and B_m as distinct physical entities. Most writers seem to regard H and B in the ether, if not entirely, yet mainly, as merely two aspects of the same quantity. Poynting, when analysing Maxwell's theory in the 1885 paper, does not even refer to the force-flux law 1. The view of Hertz is clear and drastic. In his book on waves he refers (p. 139) to " a number of auxiliary ideas which render the understanding of Maxwell's theory more difficult, partly for no other reason than that they really possess no meaning, if we exclude the notion of direct action at a distance," and in a footnote he adds " as an example I would mention the idea of a dielectric constant of the ether." He repeats his view of the needless character of this idea on page 196. He writes the circuital laws 4(c) as

$$-A\dot{\mathbf{H}}_m = \operatorname{curl}\mathbf{H}_e; \quad A\dot{\mathbf{H}}_e = \operatorname{curl}\mathbf{H}_m;$$

where A is the reciprocal of the velocity of light. He assumes that in the ether $\mathbf{H}_e$ is identical with $\mathbf{B}_e$, and also $\mathbf{H}_m$ with $\mathbf{B}_m$. He measures these in " absolute Gauss's units," so that the square of each has the dimensions of energy with

$$T_e = \frac{1}{8\pi}H_e^2 \qquad T_m = \frac{1}{8\pi}H_m^2$$

Such an aspect of the matter is not in accordance with the views of Heaviside, and really amounts to asserting that all four quantities H_e, H_m, B_e, B_m, have the same physical dimensions.

The needless additions to Maxwell's equations are discussed from a new point of view by Heaviside in his paper printed by the Royal Society in 1892. He criticizes the form of the Poynting flux of energy, and the aspects of the various fluxes occurring in Maxwell's equations. He appears to be discussing the individuality of fluxes when due to distinct energy sources. This subject is one which seems to merit more attention than has hitherto been given to it.

APPENDIX 3.

References.

Bromwich's method is given in the *Proceedings of the London Mathematical Society*, 1916, vol. 15, pp. 401–448, and is developed by H. Jeffreys in *Cambridge Tracts in Mathematics*, No. 23.

Carson's method is described in his book " Electric Circuit Theory and the Operational Calculus," 1929 (McGraw-Hill, New York). It is developed by Balth van der Pol in *Philosophical Magazine*, 1929, vol. 8, p. 861; 1931, vol. 11, p. 368; and 1932, vol. 13, p. 537.

Sumpner's papers are " Heaviside's Fractional Differentiator," *Proceedings of the Physical Society, London*, 1929, vol. 41, p. 404; " Impulse Functions," *Philosophical Magazine*, 1931, vol. 11, p. 345; and " Index Operators," *ibid.*, 1931, vol. 12, p. 201.

The subject of the individuality of fluxes, referred to at the end of Appendix 2, is discussed in " Electromagnetic Waves and Pulses," *Philosophical Magazine*, 1932, vol. 13, p. 1049.

AN ANALYSIS OF THE COSTS OF ELECTRICITY SUPPLY, AND ITS APPLICATION IN RELATION TO VARIOUS TYPES OF CONSUMERS.

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SUMMARY.

In this paper the authors' aim is to give an outline of a system of analysis of the costs of electricity supply, which is suitable for use by a large undertaking giving supply under very varied conditions to consumers of many different types.

The system described has been evolved during the last eight years in connection with the undertakings of the Newcastle-upon-Tyne Electric Supply Co., Ltd., and its subsidiary companies, and though it has not necessarily reached its final development it has at any rate passed beyond the purely experimental stage.

The paper gives an outline of the method of analysis of all costs and capital charges, but deals in greater detail with those involved by the smaller classes of consumers, the supply to whom is receiving so much attention at the present time.

A complete example of an analysis is included to illustrate the method of working.

The paper is divided into the following sections:—

(1) Reasons for cost analysis and the principles aimed at in the system described.
(2) An outline of the method of analysis.
(3) Data concerning characteristics of use of electricity by various types of consumers, required in order to apply the information obtained from the cost analysis, and the methods adopted to obtain these data.
(4) Practical applications of the analysis.

(1) REASONS FOR COST ANALYSIS, AND THE PRINCIPLES AIMED AT IN THE SYSTEM DESCRIBED.

The commodity sold by electricity undertakers is not one which lends itself to sale as simply as those articles of commerce the value of which can be expressed by such ordinary units as weight, volume, or length. What is sold is really a service or the undertaking of certain work and duties on behalf of each customer. The proper price for such service must be related both to the value of the service to the customer and to the cost to the supplier of providing the service. The cost of providing such service varies greatly under the different conditions entailed by the requirements of different customers. The unit of sale most commonly employed—or at any rate most general until recently—is the kilowatt-hour or Board of Trade unit, but the number of such units supplied bears but little relationship to the cost of the service or its value to the customer. It is for this reason that there has always (and rightly) been such a wide variation in the charge per unit for various uses.

With the extension of electricity supply to new uses and to widespread areas it is becoming increasingly realized that it is essential for suppliers to be able to estimate with comparative accuracy the relative costs entailed by various types of loads and different classes of consumers. As long ago as 1892, Dr. John Hopkinson, in his Presidential Address to the Junior Engineering Society,* said "Our complete engineer must give his attention to commercial matters as well; he must know if, when he has devised the means to attain the ends in view, those ends when attained will result in profit; he must recognize the conditions which render an undertaking economical to work and which secure that it shall bring in a large return." Dr. Hopkinson then explained the principle of dividing costs into standing or fixed and running costs, and since that date much further work has been done in applying these principles to generating costs.

TABLE 1.

Type of consumer	Generation	Distribution	Other expenses
	per cent	per cent	per cent
Large works with continuous process	69	19	12
Small works—power and lighting	43	42	15
Small house, making general use of electricity ..	32	43	25
Small house, lighting only	9	50	41

In recent times the introduction of the Electricity (Supply) Act, 1926, with its provision for the sale and purchase of electricity at selected stations on a basis of cost of production, has directed considerable attention to accurate cost analysis in relation to generating costs. This, however, takes one but part of the way, as the costs of distribution and selling must be dealt with before information of general utility can be obtained. In the case of the smaller types of supply these latter costs, which are more difficult to analyse, far outweigh the costs of generation. The figures in Table 1, for a few typical consumers, give an indication of the relative value of the costs and capital charges due to generating and distribution and of other expenses incurred in the supply of electricity, such as meter reading, accountancy, and management.

The fact that it is seldom, if ever, satisfactory or practicable to sell upon a pure cost basis, as the proper price of any commodity is governed more by its value to the customer (which must ultimately be realized to be

* Now the Junior Institution of Engineers.

true even under a national scheme), is no reason for neglecting a careful consideration of cost, so that the necessary departures therefrom may be made with knowledge and intention and not in a haphazard manner.

The principle, therefore, which has been kept in view in this analysis of electricity costs is that each class of supply should be debited with its true proportion of every item of cost, so that a sound basis may be obtained on which development can be built. Particular care is taken to avoid crediting any type of supply with advantages of a temporary nature, such as a smaller proportion than its permanent share of any capital costs, arising for instance from the existence of spare capacity for the time being, or such considerations as the precise hour of peak load during recent years. Temporary conditions of this nature may enable certain load to be taken on profitably at a reduced figure for the time being, but if this is done the difficulty of adjustment to a correct figure later when such temporary conditions pass away has to be faced.

(2) AN OUTLINE OF THE METHOD OF ANALYSIS.

The system of cost analysis to be described in this paper can be roughly divided into three stages:—

(1) The division of annual costs and of capital expenditure under a sufficient number of suitable headings, and the allocation of the item under each heading as a fixed charge or running cost, or its further division so as to allocate part as a fixed charge and part as a running cost.

(2) The division of consumers into three main groups in accordance with the general conditions under which they take supply, and the allocation of the costs and capital expenditure divided as above between these groups.

(3) The analysis of the costs and capital expenditure allocated to each group, and the evolution of formulæ suitable for application to individual members of each group.

It will be noted that capital is dealt with by the allocation of the amount of capital expenditure instead of by the more usual method of treating capital charges as an item of overhead expenses. The expression "overhead costs" used later in the paper is exclusive of capital charges.

The method adopted has been found more convenient in practice as the figures obtained by it have a wider application of use than figures involving the assumption of rates of interest and depreciation.

Division of Annual Costs and of Capital Expenditure Under Suitable Headings.

For the purposes of this analysis it has been found desirable to keep annual costs and capital expenditure under a considerably greater number of headings than those required for such official returns as are made to the Electricity Commission or the Board of Trade.

For instance, in the case of distribution, costs entailed in connection with high-voltage distribution are kept distinct from those incurred in connection with low-voltage networks, and, in the case of salaries and wages in the consumers' departments, those relating to the staff who deal with lighting and domestic consumers are kept distinct from those of the staff who deal with power supplies.

Headings under which annual costs are kept are set out in the first column of Appendix 2 (1). In addition to the items tabulated in this Appendix there are certain items which cannot fairly be debited to current supply and which should be covered by revenue received other than from the sale of energy. Typical instances are:—Repairs and maintenance of public lamps, consumers' installations, and apparatus hired to consumers.

The headings under which the capital expenditure is divided follow as far as practicable the appropriate headings used for costs, but in many instances the division of capital has proved more difficult. This is chiefly owing to the fact that, whereas costs are transitory and a fresh start can be made in any year under an improved system of accounting, capital expenditure is cumulative and any change in method involves research into earlier years in order that past capital expenditure may be re-divided under the new headings.

The headings under which it has been found practicable to subdivide capital expenditure with comparative accuracy are given below, the items being capable of further division between land, buildings, and plant, where such division is applicable. Still further subdivision might be of some advantage if it could reasonably be done, but the subdivisions given have proved sufficient to enable the system of analysis described to be carried out.

Generating stations.
High-voltage interconnecting substations.
High-voltage interconnecting mains.
High-voltage transmission and distribution substations.
High-voltage transmission and distribution mains.
Low-voltage distribution substations.
Low-voltage distribution mains.
House services.
Meters (other than in power stations or substations).
Office buildings and equipment.
Motor vehicles.
Test house and equipment.
Acts and Orders.

In addition to the items detailed above there is expenditure on reserve coal stocks and stores to be taken into account. There are also inevitable small items of capital expenditure which cannot readily be classified under any of the above headings and must come under some such heading as "Miscellaneous" and be allocated in a more or less arbitrary fashion, but with care the amount represented by such items can be kept to such a low figure as not to have an appreciable effect on the final results.

Having divided costs and capital expenditure in the above manner, the next step is to consider each item in the light of whether it (or the charge on it in the case of capital expenditure) constitutes a "fixed charge" or a "running cost," or whether it must be further divided between the two.

In "running costs" are included all those costs which

depend upon the number of units sent out from the generating stations.

Costs and charges which depend upon the kilowatt demand made upon the stations, or on some other factor independent of the number of units, are regarded as "fixed charges."

With one exception all capital charges and all costs other than generation working costs are regarded as fixed charges. The exception is that of interest on money invested in reserve coal stocks, as the necessary quantity of such stocks depends mainly on the output of units.

The division of generating costs into fixed charges and running costs has recently been investigated in considerable detail in connection with the allocation of costs of production at selected generating stations called for by the 1926 Act, and included in Appendix I are the formulæ for this purpose which have been published by the Electricity Commissioners, together with curves resulting from the formulæ. These, of course, are intended to represent average conditions for selected stations, but they are in reasonable agreement with the results of the authors' own investigations on a limited number of stations, except in the case of repairs and maintenance, where the Electricity Commissioners' formula allocates a somewhat larger proportion as fixed costs than the authors' information suggests to be correct.

The analysis has now reached the stage when the costs and capital expenditure are divided under the required headings and each item is to be allocated either as a fixed cost or a running cost, or is split into two parts, one part to be allocated as a fixed cost and the other part as a running cost.

Allocation Between Main Groups of Consumers.

The next step is to allocate or divide each item between different classes of consumers.

For this purpose consumers are classified under three main or primary groups:—

Group A. Consumers taking a supply of considerable magnitude at the power station site.

Group B. Consumers supplied from the high-voltage system.

Group C. Consumers supplied from the low-voltage networks.

Fig. 1 illustrates these groups, and the principles of allocation are dealt with more fully in Appendix I. By means of the detailed division of cost and capital expenditure under the various headings given earlier, it is possible to allocate a considerable number of items directly to one or more of these groups. Where such direct allocation is not possible it has been found necessary to give careful consideration to each item of cost or capital expenditure and frequently to undertake further analysis of the item, in order to determine the basis on which it should be divided between the three groups.

The two bases of division most usually adopted, i.e. demand and units, have not been found by any means sufficient and many other factors have been introduced, such as number of consumers of different types, capital expenditure on particular kinds of supply, salaries and wages of employees concerned, area of office accommodation required by staff concerned, etc. These factors are necessarily of a somewhat arbitrary nature, as they are arrived at by argument and deduction, though it is possible in many cases to test their correctness by comparison between different areas of supply and the results for different years. Where it is not possible to find a single factor which can be regarded with reasonable accuracy as controlling any particular item of the cost, a special investigation into such item is made every few years by splitting it into as small components as practicable, scrutinizing each component with a view to its proper allocation between the three groups, and so arriving at a percentage allocation basis for the item of cost as a whole.

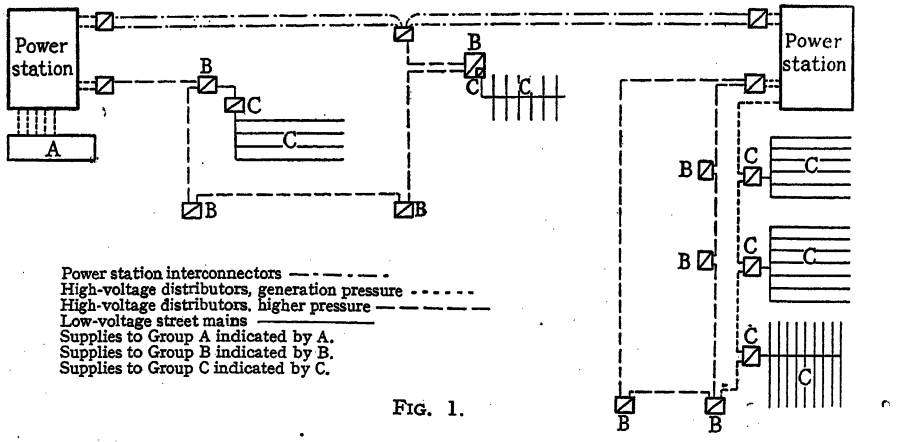


Fig. 1.

For the allocation between groups of those items depending on demand, the demand is taken in kilowatts and not in kilovolt-amperes. Although the majority of items depending upon demand are more strictly proportional to kilovolt-amperes, this method has been found sufficiently correct, as there is little difference in the power factors of the groups as a whole. While the lighting and heating load in Group C tends to raise the power factor of the group, the "small motor" load tends to lower it, as does also the plant at the distribution substations, which in many cases is unavoidably of considerably greater capacity than the load for the time being.

In Appendix II (1) tables are given showing the basis

on which the various items of cost are allocated between these three groups, and in Appendix II (2) are similar data for capital expenditure. There are certain items of both cost and capital expenditure the allocation of which is too involved to be given in the limited space available in the tables. The allocation of these items, together with explanatory notes, is shown in Appendix II (3).

Analysis of the Costs and Capital Expenditure Allocated to Each Group, and the Evolution of Formulæ Suitable for Application to Individual Members of Each Group.

Having allocated the costs and capital expenditure between these three primary groups of consumers, there remain the analysis of the amounts debited to each group and the evolution of the three distinct sets of costing formulæ which can be applied to the various types of consumers within the three groups.

The form into which the costs are resolved is necessarily determined by the manner in which it is proposed to use the figures obtained. This is referred to later under "Practical Application of the Analysis," but the main purposes for which the formulæ are required are to estimate the financial results which will accrue from extension of business into new areas or by the development of particular types of supply, to form a basis on which tariffs for different kinds of load can be built, and generally to enable a simple statement to be readily made as to the economic merits of any of the many and varied problems which arise in connection with electricity supply. With these aims in view, taking each group in turn, the amount of each item allocated to the group is reviewed with the object of its division among members of that group on the basis of (*a*) units taken per annum by an individual member, (*b*) one or more specified demands made by such member, and (*c*) a charge per point of supply.

It will be noted that the large variety of factors introduced in the earlier allocation between the primary groups is no longer required, as the conditions within each group are sufficiently similar to allow of division of costs and capital expenditure between the members of the same group by means of a formula containing only the factors named above. The working formula thus obtained for each group is one of which the variables are limited to characteristics which can be determined in practice for any particular type of consumer.

Details of this analysis of the costs and capital expenditure allocated to each group are given in Appendix III.

In the analysis of the capital expenditure allocated to each group the expenditure which is incurred especially on account of an individual consumer and is not common to the general group is kept separate from the rest of the formula, and when considering a particular consumer the actual expenditure applicable to him only is added as the final item of capital. For the sake of convenience such expenditure is referred to as "Special capital expenditure" and the proportion of common expenditure as "General capital involved," while the two together are designated "Total capital involved." It is on this last figure that the percentage returns arising from different tariffs and supplies are calculated and th profits compared.

In the case of Group A consumers the problems arising are usually quotations for supplies of considerable magnitude which deserve very special consideration. The analysis forms a useful basis for any calculations that may have to be made, and may be used for framing replies to urgent requests for quotations for large supplies at high load factor; these are not infrequently received, but they much less frequently materialize.

The analysis of cost for these consumers should present little difficulty, as little more than generation costs are concerned. Where two or more power stations are included any special high-voltage lines performing the duty of power-station interconnection should be included.

The analysis of Group B (consumers supplied from the high-voltage system) is a little more involved, and the formula evolved by analysis is expressed as:—

Costs per annum = sum of

(1) £ per kW of demand made on the power stations.
(2) £ per point of supply.
(3) Pence per unit delivered to the high-voltage busbars at the consumer's substation.

Capital involved = sum of

(4) £ per kW of demand made on the power stations.
(5) £ per point of supply.
(6) £ special capital (this being the value of any substation apparatus and high-voltage mains used only to supply this consumer).

It should be noted that, in general, no allowance is made for distance from the power stations, although the system is sufficiently elastic to allow of allocating to any consumer expenditure above normal on mains used for his supply.

The demand is expressed as "demand made on the power stations" so as to allow of a proper adjustment being made to the demand as metered at the consumer's premises to take account of diversity. A fixed diversity factor is not used, the demand on the power stations being calculated in each case by the application of an efficiency factor and a variable diversity factor (normally between 1 and 1·5), depending on the load factor and other relevant conditions of the supply in question.

The demand costs are for convenience expressed as £ per kW rather than £ per kVA, as the former figure is generally more readily ascertainable, but where the power factor differs appreciably from the average for the group an adjustment on this account is required. This is not difficult to make, as the items of cost and capital expenditure dependent on kilovolt-amperes rather than kilowatts are fairly easily distinguishable.

The unit cost can be conveniently expressed as cost per unit delivered to the high-voltage busbars at the consumer's substation, as the question of diversity does not here arise. It thus takes account of average losses between the power stations and the substations, the only necessary adjustment to units sold being those for losses between the point of metering and the high-voltage busbars in the substation.

The analysis of the cost of supply to the smaller consumers coming under Group C provides much more scope for investigation because the distribution is carried further and supplies are afforded to a multitude of different types of consumers for a large variety of purposes; furthermore, some of the loads are intermittent, some regular, and some seasonal; and each involves a separate problem of load factor and diversity.

The difference in power factor between various members of the group is also considerable, and for this reason the demand charge in the formula is based on kVA.

This introduces the necessity for a factor for use as a divisor in arriving at the amount per kVA in order to compensate for the error introduced by arithmetical addition of kVA, the sum of simultaneous kVA demands at differing power factors being greater than the combined kVA demand resulting from them. This factor depends upon the proportion of load at various power factors and in ordinary practice lies between 1·05 and 1·1 for a.c. networks supplying general load.

The formula for this group is less simple, but only some of the figures in it are used in any particular problem.

In addition, the application of the formula requires specially-prepared technical data.

The formula is as follows:—

Costs per annum = sum of

(1) £ per kVA of "effective demand" occurring during the period of heavy load on the high-voltage system and power stations.

(2) £ per kVA of "effective demand" occurring during the period of heavy load on the low-voltage networks.

(3) pence per unit sold to the consumer.

(4) (*a*) £ per consumer for lighting and domestic consumers on quarterly or monthly accounts.

(*b*) £ per consumer for consumers supplied through prepayment meters.

(*c*) £ per consumer for consumers taking a supply for industrial power purposes.

Capital involved = sum of

(5) £ per kVA of "effective demand" occurring during period of heavy load on the high-voltage system and power stations.

(6) (*a*) £ per kVA of "effective demand" occurring during the period of heavy load on the low-voltage networks, for use when considering existing supplies.

(*b*) £ per kVA of "demand" as for 6 (*a*), for use when considering supplies involving extensions of low-voltage networks.

(*c*) £ per kVA of "demand" as for 6 (*a*), for use when considering supplies involving expenditure on a complete network, including a new sub-station.

(7) (*a*) £ per "standard domestic consumer" supplied from existing networks.

(*b*) £ per "standard domestic consumer" where supply involves provision of low-voltage mains.

(*c*) £ per consumer for shops, offices, etc., supplied from existing networks.

(*d*) £ per consumer for shops, offices, etc., where supply involves provision of low-voltage mains.

(*e*) £ per consumer for works and factories supplied from existing networks.

(*f*) £ per consumer for works and factories where supply involves provision of low-voltage mains.

(8) £ special capital, being the cost of the service apparatus and connection, and the meter.

The above list of factors may seem formidable but the formula is easily applied in practice; in fact the majority of routine work involving its use can readily be performed by an intelligent clerk having no special engineering knowledge.

The whole process of the cost analysis may be summarized as follows:—

The total costs and capital expenditure are taken. Those costs and capital expenditure not strictly attributable to electricity supply are extracted.

The remaining costs and capital expenditure are allocated to those consumers responsible, the consumers having been grouped into three sections.

The costs and capital expenditure for each section are considered item by item and expressed as factors of £ per kW or kVA of demand, £ per consumer or pence per unit; like factors are then collected into the shape of formulæ for application to problems.

A complete example of an analysis is given in Appendix IV. The figures used are merely to demonstrate the method and do not relate to the costs of any particular undertaking.

(3) DATA CONCERNING CHARACTERISTICS OF USE OF ELECTRICITY BY VARIOUS TYPES OF CONSUMERS, REQUIRED IN ORDER TO APPLY THE INFORMATION OBTAINED FROM THE COST ANALYSIS, AND THE METHODS ADOPTED TO OBTAIN THESE DATA.

In order to apply to any particular consumer or consumers the formulæ derived from cost analysis, it is necessary to have information as to his or their use of electricity. This information must include the annual consumption in kWh and the demand or demands which are to be applied to the figures in the formulæ.

In the case of existing consumers the consumption is a figure which is practically always known, while with new consumers a close estimate is usually available in the case of large consumers, and experience gives an average figure for the smaller ones.

In Appendix V tables are given which include average yearly consumptions based upon large numbers of small consumers of various types, which may be regarded as typical, although variations may occur in different parts of the country.

The demand or demands to be used are much more difficult to arrive at, as here the factor of diversity is at once introduced, acting in opposition to load factor.

A group of consumers, each of low load factor individually, may, as a group, have a comparatively high load factor owing to the individual maximum demands occurring at different times, or in other words owing to

a high factor of diversity. Obviously, in a group of consumers, each with a high individual load factor, there is less opportunity for individual demands not to coincide and a high diversity factor is not possible. In the extreme case of a group of consumers, each with 100 per cent load factor, there can clearly be no diversity.

Although there is difference of opinion on the question of peak-load responsibility, there is no great difficulty in arriving at the demands to be taken in the case of the more usual types of larger consumers where supply is taken over a considerable period during each working day, and sufficient motors and other plant are installed to give a more or less definite and constant load curve. The question of consumers making the whole or the chief part of their demand at night or in summer time is more difficult, and requires individual consideration.

As soon, however, as analysis is extended to the smaller class of consumers, such as domestic consumers, shops, or consumers with a few small motors, the effect of diversity becomes of primary importance, and without considerable data concerning diversity and its influence it is impossible to proceed very far.

In order to arrive at the demands in such cases after the factor of diversity has been taken into account (which demands the authors have termed the "effective demands"), a considerable amount of special investigation has been carried out.

In Appendix VI the load curves given in the paper are discussed, and it is shown how these "effective demands" for small consumers have been determined. The method adopted for obtaining these curves is as follows:—

Consumers are divided into classes according to their type of business and other considerations, and recording ammeters are installed simultaneously at the service points of a number of consumers of the same class. A record is then obtained of the current taken by each consumer over a period, the length of which depends upon the constancy of conditions.

In certain cases it has been found possible to install the recorders on a feeder supplying consumers of one class only, e.g. a group of small houses with similar apparatus installed, but obviously it is only in a comparatively small number of cases that it is possible to obtain a feeder which supplies one class exclusively.

The charts obtained from the recorders are then analysed into half-hourly demands expressed in kVA, and the resultant half-hourly demands for each day from Monday to Friday are superimposed one on another, and an average weekday load curve is obtained.

The curves for all the consumers are then superimposed and an average weekday load curve is obtained for this class of consumer, which allows for diversity between its members.

The process is continued until the curve assumes a definite shape which is practically unaffected by superimposing further individual curves.

An example of the process is given in Appendix VII.

This method does not lend itself to the determination of general diversity factors with a wide application, and, in the authors' opinion, great discretion is needed in the use of a diversity factor obtained under one set of conditions unless it is quite definite that the same conditions obtain in the problem under consideration. Possible exceptions are diversity factors referring to areas or districts, involving a factor (expressed as sum of individual demands divided by simultaneous demand) of less than about 1·3.

The average demands over those periods of the day during which the peaks firstly on the generating stations and high-voltage distribution system, and secondly on the low-voltage distribution networks, are liable to occur, are used for determining the "effective demands." Some values of "effective demand" ascertained in this manner are given in Appendix V.

(4) PRACTICAL APPLICATION OF THE ANALYSIS.

As has already been mentioned, the principal purposes for which the formulæ are used are:—

(1) Estimating the financial results which will accrue from the connection of new supplies.
(2) Forming a basis on which tariffs can be built.
(3) Enabling consideration to be given readily to the economic merits of various problems as they arise.

For the first of these purposes a regular routine has been adopted by means of which a profit-and-return statement is prepared in connection with any proposed extension to the distribution system before expenditure is approved. Copies of some of the forms used for this purpose are given in Appendix VIII.

The adoption of a standard system of assessing profit on all supplies, besides being a guide towards sound expenditure, has the merit of facilitating equitable treatment of different consumers.

In the consideration of tariffs, the analysis is of great assistance as it enables curves showing cost at different consumptions, load factors, etc., to be readily drawn for any type of supply. Although a tariff framed on a pure cost basis is seldom practicable, a theoretical tariff of this nature forms a basis which can be simplified and modified into a useful form.

Some views on tariffs rather contrary to those frequently accepted arise from a study on these lines. One of these is that it is not correct to assume that the unit charge in a two-part tariff suitable for domestic supplies will be correct for other supplies such as, say, those to shops. This is because it is not suitable in practice to make the unit charge as low as the theoretical cost varying with units, as to do so would not only make the price to short-hour users higher than is practicable but would be inequitable unless the factor governing the fixed portion of the charge was one which took proper account of diversity. As such factors are not available, it is more correct, as is customary, to make the unit charge greater than its theoretical value so that it will cover part of the cost depending on demand, and to reduce the fixed part of the charge correspondingly. By choosing a suitable increase to the unit charge a reasonable corrective for the effect of varying diversity can be automatically obtained for a particular class of consumer, but the amount of increase so required varies with different classes.

Another point is that for domestic supplies a two-part tariff consisting of a fixed charge (calculated on floor area, number of rooms, rateable value or some such factor) and a single charge per unit only gives a good representation of cost over very limited ranges of consumption, and such a tariff can be much improved by the substitution of a sliding-scale unit rate for the single-unit charge, the steps of the scale being governed by the same factor as that which governs the fixed charge.

Again, in the case of small power supplies from low-voltage networks it will appear from a study of cost analysis that a simple sliding-scale unit tariff is probably more correct from a cost point of view than any two-part tariff in which one of the charges is based on demand, kilowatts connected, rateable value, or some such factor.

In addition to the above, the analysis has been found of the greatest value in the consideration of all sorts of problems, as it provides in a useful form a definite basis on which to make comparisons of the economic merits of alternative schemes without having to refer to first principles in each case.

APPENDIX I.

Allocation of Costs and Capital.

By allocation of costs is meant the tabulation of items of cost or parts of items of cost in separate groups under the headings of the types of consumers in respect of whom the costs are incurred. A similar definition applies to allocation of capital.

This allocation is a preliminary to the process of analysis and the evolution of costing formulæ. It has been found from experience that it is a great help to consider allocation and analysis as two separate and distinct processes; this enables the essentials to be more clearly seen and by concentrating on the allocation as an aim in itself the process is performed more thoroughly.

The method of allocation naturally depends upon the form in which the costs are required for analysis, this again depending on the way it is proposed to apply the results of analysis.

The object of cost analysis is mainly the solution of problems connected with the following types of consumers:—

(1) Large consumers fed directly from power stations.
(2) Other large consumers supplied at high voltage.
(3) Small power consumers supplied from low-voltage networks.
(4) Shops and business premises, etc., supplied from low-voltage networks.
(5) Houses with monthly and quarterly accounts.
(6) Small domestic consumers supplied through prepayment meters.

It is with these consumers in mind that the method of allocation is decided upon.

In Appendix II will be found a table which gives in condensed form the allocation applied to each of the more important items, and in order to make this table clearer certain principles on which the allocations have been made and the reasons which have led to these decisions are given here.

The costs referred to are in all cases the costs for a calendar year.

Generation Costs.

It has been well known for many years that the fuel cost of a power station can be fairly accurately divided into "fixed costs" and "running costs" (the former being independent of the units generated and the latter directly proportional to the units). This division enables the fuel cost to be predicted for conditions of load which differ from those obtaining during the period under investigation.

This system of division into "fixed" and "running" costs has been recognized in recent years as extending to all the main items of generation costs.

The formulæ adopted by the Electricity Commissioners for application to the cost of production at selected generating stations are quoted below and are also depicted in graphical form in Fig. 2.

In all cases the formulæ* state in algebraic terms that the percentage of the cost which is fixed varies inversely as the load factor.

The following is an extract from the Regulations in question:—

"Formulæ for ascertaining the portion of certain costs, charges and allowances to be allocated as fixed costs.

Cost of Fuel.

$$\text{Portion to be allocated as fixed costs } \frac{100}{100 + 12{\cdot}8L}$$

Cost of Oil, Water, and Stores.

$$\text{Portion to be allocated as fixed costs } \frac{100}{100 + 9{\cdot}66L}$$

Salaries and Wages.

$$\text{Portion to be allocated as fixed costs } \frac{100}{100 + 0{\cdot}38L}$$

Cost of Repairs, Maintenance, and Renewals.

$$\text{Portion to be allocated as fixed costs } \frac{100}{100 + 0{\cdot}0001NL}$$

where L is the average load factor of the station, as defined in Regulation 2; and N is the number of hours during which the station was in commission in the year of account."

The definition of average load factor referred to is expressed as a percentage, and is

$$\frac{\text{Units for the year} \times 100}{\left.\begin{matrix}\text{Average monthly maximum} \\ \text{demand}\end{matrix}\right\} \times \left\{\begin{matrix}\text{number of hours station} \\ \text{was in commission}\end{matrix}\right.}$$

By applying the formulæ, the generating costs are divided into "fixed" and "running" costs, the fixed costs being those which are deemed to depend on the

* See Statutory Rules and Orders, 1929, No. 1015.

demand on the station and are fixed only inasmuch as they do not increase in proportion to the units generated.

Actually the "fixed" costs are probably more dependent on the size of the power station and the capacity of the plant which is in use than on the demand, but they can with very fair accuracy be allocated in proportion to the demands made on the power station by each of the three groups of consumers.

The "running costs" are dependent on the units generated and are therefore allocated in proportion to the units sent out for sale to each of the three groups of consumers.

In cases where electricity is purchased in bulk the form of the tariff under which it is purchased must be taken into consideration, and the charges divided into "fixed costs" and "running costs" before the allocation can be correctly performed.

A bulk supply taken on a demand-and-unit tariff is an obvious instance where this principle can be easily applied. The authors suggest that even where the tariff consists of a flat unit rate it is equally important that a suitable division should be made as any flat unit rate should from time to time be revised, taking load factor into consideration, and therefore the development of high-load-factor business—even at prices below the unit rate paid for the time being—may be justified.

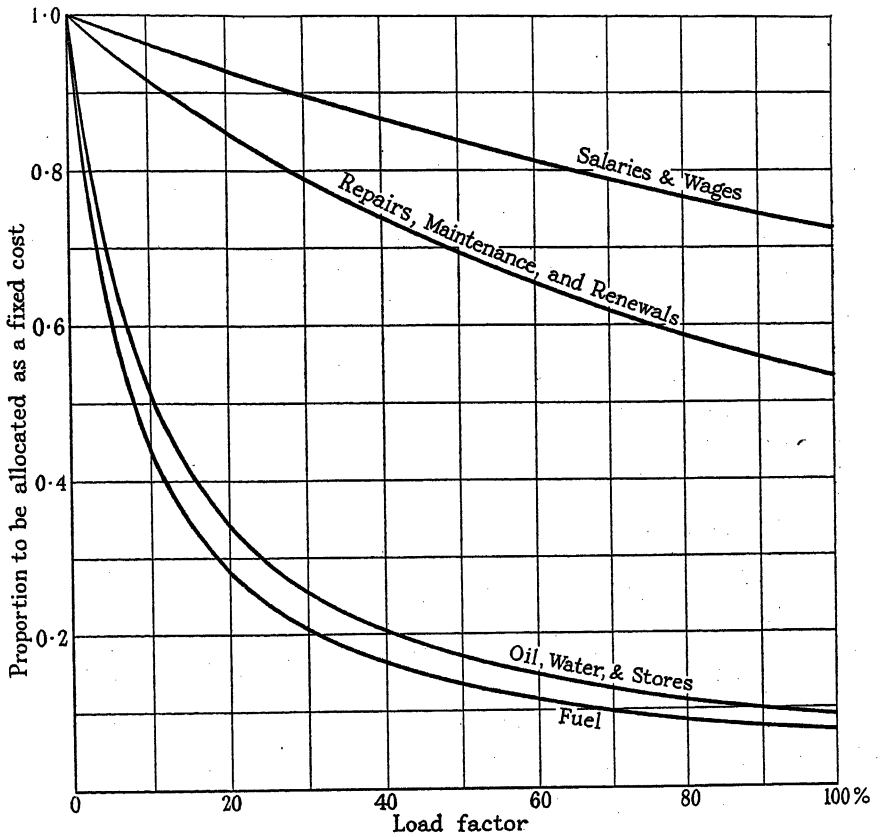


FIG. 2.—Allocation of cost of production at selected generating stations (Statutory Rules and Orders, 1929, No. 1015).

Substations.

In order that repairs, maintenance, and other work carried out on substations may be allocated to either high-voltage or low-voltage distribution, each substation is placed in one of the five standard categories shown in Table 2.

The definitions of high voltage and low voltage as applied to substations are not so much concerned with the magnitude of the voltages as with the work that the substation performs.

TABLE 2.

Category	Allocation of costs	
	To high voltage	To low voltage
	per cent	per cent
High voltage	100	nil
High voltage and low voltage "A"	75	25
High voltage and low voltage "B"	50	50
High voltage and low voltage "C"	25	75
Low voltage	nil	100

The allocation of capital expenditure on substations

can only be done with fairness and accuracy by a close examination of the purposes for which each substation is used.

The expenditure can usually be allocated under one or more of the following headings:—

(*a*) Expenditure involved in high-voltage transmission,
(*b*) Expenditure involved in giving supplies to low-voltage networks.
(*c*) Expenditure involved in giving supply to an individual consumer.

The sample form given in Table 3 shows how substation allocations are recorded. For ease of reference they are compiled in alphabetical order.

TABLE 3.

Name of substation	Amount	Allocation		
		To high-voltage transmission	To low-voltage distribution	To individual consumer
	£ s. d.	£ s. d.	£ s. d.	£ s. d.
Banston	4 837 7 6	2 500 0 0	1 337 7 6	1 000 0 0
Barker and Co.	576 5 0	—	—	576 5 0
Bursey Village	138 8 0	—	138 8 0	—
Cathill Colliery	3 200 11 0	1 400 0 0	—	1 800 11 0

High-Voltage Transmission and Distribution.

Several items are allocated on what is referred to as a "High-voltage distribution basis," a detailed explanation of which is as follows.

The high-voltage distribution costs considered as a whole form a fairly large item, and require special consideration in order that they may be allocated with reasonable accuracy between classes of consumers. In some areas high-voltage networks have been extended into country districts to supply collieries, ironstone mines, quarries, and other power consumers requiring supplies of sufficient magnitude to justify high-voltage lines of considerable length. These lines are often used to give supplies to villages and farms *en route*, supplies which are of small size and which would not have been given unless the supply had already been available in the district.

In other areas which are thickly populated, the high-voltage lines are short and feed a number of step-down substations grouped closely round the power station.

It was decided that high-voltage distribution costs could not be fairly allocated between the groups of consumers merely by dividing them in proportion to their respective demands, and a method was devised which would take some account of the conditions which have just been referred to.

The basis of allocation is founded on the assumption that high-voltage distribution costs are roughly in portion to the capital value of the mains. (This ption is only claimed to be fairly accurate for the for which it is used.)

pital expenditure on high-voltage mains was to two portions, (*a*) that relating to mains supplying substations in the densely populated areas adjacent to the power stations, and (*b*) that relating to mains supplying substations outside these areas.

The capital expenditure on high-voltage mains in each of these two portions in turn was then allocated between the groups in proportion to their demands, the demand having been subdivided in a similar manner.

This analysis may seem somewhat involved, but the following example of such an analysis will enable the argument to be followed.

(1) *Expenditure on High-Voltage Mains.*

(*a*) Within the densely populated areas ..	£200 000
(*b*) Outside these areas	£800 000
Total	£1 000 000

(2) *Demands on High-Voltage System.*

(*a*) Demand of Group B within the densely populated areas	30 000 kW
Demand of Group C within the densely populated areas	20 000 kW
(*b*) Demand of Group B outside these areas	70 000 kW
Demand of Group C outside these areas	1 000 kW

(3) (*a*) *Allocation of Expenditure within the densely populated areas.*

To Group B allocate $\frac{30\,000}{50\,000}$ of £200 000 = £120 000

To Group C allocate $\frac{20\,000}{50\,000}$ of £200 000 = £80 000

(*b*) *Allocation of Expenditure outside these areas.*

To Group B allocate $\frac{70\,000}{71\,000}$ of £800 000 = £788 720

To Group C allocate $\frac{1\,000}{71\,000}$ of £800 000 = £11 280

Amount allocated to Group B = £120 000
+ £788 720 = £908 720

Amount allocated to Group C = £80 000
+ £11 280 = £91 280

If the allocation had been made on the basis of the total demands, without reference to area, the result would have been:—

To Group B $\frac{100\,000}{121\,000}$ of £1 000 000 = £826 400

To Group C $\frac{21\,000}{121\,000}$ of £1 000 000 = £173 600

In arriving at the demands used for this allocation, a special allowance is made for diversity.

As the distribution mains under consideration stretch from the power station to the distribution substations, the maximum demands at the substations will not occur simultaneously and will result in a maximum demand at the power station which will be less than the sum of the maximum demands at the substations.

It is obvious that this diversity arises between the substation and the power station, and is due to the junction of loads into common mains. Therefore, considering the mains throughout their whole length, the average diversity factor throughout a main will be less than the full factor between substations and power station.

For the purpose of the above allocation, therefore, the effective demands are obtained by dividing the sum of the substation demands by a " half diversity " factor (for instance 1·2 instead of 1·4).

This allocation, which has been made of the capital expenditure involved in high-voltage distribution, provides allocation percentages which are used for various items of high-voltage transmission and distribution cost and capital, the costs for this purpose being, as previously stated, assumed to be proportional to the capital.

Low-Voltage Distribution.

The costs and capital expenditure involved in low-voltage distribution naturally only concern the consumers supplied from the low-voltage networks, and are therefore allocated in their entirety to this group of consumers. The sub-allocation of these items to different types of small consumers is considered in the description of the analysis.

Overhead Costs.

The items under " Overhead Costs " in nearly all cases have individual methods of allocation which have been arrived at by special investigation in collaboration with the heads of the departments concerned, or other persons having special knowledge of the circumstances. In most cases the percentage allocation so arrived at can be used without revision for several years and the work involved by such special investigation is consequently not excessive.

National Health and Unemployment Insurance are not included here, but are allocated with the wages to which they refer. A similar principle is as far as possible adopted throughout with regard to Pensions Fund contributions and personal and other petty expenses.

With regard to the items under " Other costs " and " Miscellaneous charges," in every case the items are considered individually and allocated with the care that is merited by the magnitude of the amount concerned. In the case of a number of small items, these may on one occasion be allocated individually, then summarized as a group, and in following years they may be allocated as a group on the percentage previously determined.

[*Further Appendices will be found on pages* 862–893.]

APPENDIX II (1).

METHOD OF ALLOCATION OF COSTS TO THE THREE MAIN GROUPS OF CONSUMERS.

Item of cost	How allocation between groups is made	
	of the fixed proportion of cost	of the running proportion of cost
Working Costs.		
(*a*) *Generation*		
Fuel	In proportion to the demands of the three groups on the power stations	In proportion to the units sent out of the power stations in respect of each group
Fuel-handling		
Ash-handling and disposal		
Steam or waste heat purchased		
Current purchased		
Water		
Oil and stores		
Salaries and wages (operation)		
Repairs and maintenance		
(*b*) *High-voltage Transmission and Distribution.*		
Salaries and Office wages	On high-voltage distribution basis (see Appendix I)	
High-voltage interconnection (operation costs)	In proportion to the demands of the three groups on the power stations	
High-voltage interconnection (repairs and maintenance of substations)		
High-voltage interconnection (repairs and maintenance of mains)		
High-voltage transmission and distribution (operating costs)	This item is subdivided and allocated between Groups B and C in a special manner (see special allocation)	
High-voltage transmission and distribution (repairs and maintenance of substations)	On high-voltage distribution basis	
High-voltage transmission and distribution (repairs and maintenance of mains)	On high-voltage distribution basis	
(*c*) *Low-voltage Distribution.*		
Salaries and office wages	Allocated entirely to Group C	
Operation of substations		
Repairs and maintenance of substations		
Repairs and maintenance of mains		
Repairs and maintenance of house services		
Repairs and maintenance of meters		
Overhead Costs.		
(*a*) *Management and Departments common to General Business.*		
Management: Proportion corresponding to time devoted to consumers	Arbitrary basis on estimated time spent in connection with consumers of each group	
Proportion devoted to other matters	In proportion to the capital expenditure allocated to the three groups	
Secretary's department	This item is subdivided and subjected to special allocation; the basis is explained in special allocation	
Accountant's department		
Cashier's department	Same remarks as for Accountant's department apply to these items	
Statistical department		
Testing department	This item is subjected to special allocation	
Transport department	Transport charges are kept in detail and are added to the other items with which they are associated and allocated with them	
Consumers' departments:—		
(1) Lighting and domestic	Allocated entirely to Group C	
(2) Colliery supplies	Allocated entirely to Group B	
(3) General power supplies	A special allocation is made of the salaries and wages of the staff between the three groups	
Showrooms and Branch Offices	Allocated entirely to Group C	
(*b*) *Other Costs.*		
Rents	Allocation depends on purpose for which each rental is paid	
Rates	In proportion to the capital expenditure allocated to the three groups	
Taxes	In proportion to capital expenditure (as above)	
Insurances (other than National Health, etc.)		
Payments for wayleaves	On high-voltage distribution basis	

APPENDIX II (1).

METHOD OF ALLOCATION OF COSTS TO THE THREE MAIN GROUPS OF CONSUMERS—*continued.*

Item of cost	How allocation between groups is made
(*b*) *Other Costs—continued.*	
Telephones (maintenance and operation of private system)	Subdivided between generation, distribution, and office, and subject to special allocation
Electricity Commissioners' charges	In proportion to units sent out of power station in respect of groups (excluding supplies to authorized distributors)
Standardization-of-frequency levy	In proportion to revenue received from the three groups (excluding supplies to authorized distributors)
(*c*) *Miscellaneous Charges.*	
Directors' fees	In proportion to capital expenditure allocated to the three groups
Stock trustees	
Auditors	In proportion to revenue received from the three groups
Legal advisers	Allocated on an arbitrary basis according to experience
Bank	In proportion to capital expenditure allocated to the three groups
(*d*) *Other Miscellaneous Expenses.*	
Stationery and printing	Allocated on number of consumers in each group, adjusted by factors for different types of consumers
Stamps and telegrams	
Advertising	Allocated on an arbitrary basis
Subscriptions and gratuities	Allocated in proportion to the revenue received from the three groups
Recreation club, welfare, etc.	

APPENDIX II (2).

METHOD OF ALLOCATION OF CAPITAL EXPENDITURE.

Item of capital expenditure	How allocation between groups is made
Generating stations	In proportion to the demands of the three groups on the power stations
High-voltage interconnecting mains	
High-voltage interconnecting substations	
High-voltage transmission and distribution mains	On high-voltage distribution basis
High-voltage transmission and substations	Each substation is considered separately; the proportion concerned with general high-voltage distribution is allocated between groups in the same proportion as high-voltage mains
Low-voltage distribution mains	Allocated entirely to Group C
Low-voltage distribution substations	
House services	
Meters (other than in power stations or substations)	
Office buildings and equipment	A special allocation is performed between departments, taking into consideration the space occupied, furnishing, and equipment; allocation is then made as for costs of departments
Motor vehicles	In proportion to transport costs
Test house and equipment	Special allocation
Acts and Orders	Allocated on arbitrary basis to the three groups

APPENDIX II (3).

SPECIAL ALLOCATIONS.

Explanation of Special Allocations Referred to in Appendix I.

High-voltage Transmission and Distribution.

Operation costs.—This item is divided into two parts and allocated as follows:—

(1) Operation of substations, cost of material; allocated on high-voltage distribution basis.

(2) Operation of substations, wages; allocation is best expressed in diagrammatic form as follows:—

Operation of Substations, Wages.

Divided in ratio of number of substations operated.

Number of consumers' substations.	Number of company's substations.
To Group B only and divided for analysis.	Allocated between Group B and Group C on high-voltage distribution basis.
½ per point of supply.	½ per kW. Group B portion analysed per kW. Group C portion analysed per kW.

Accountant's Department.

The salaries and wages are divided between:—

(1) Current supply.
(2) Purchases.
(3) Sundry works, stores, etc.

Each of the above is considered separately and allocated to the three groups.

Cashier's Department.

The salaries and wages are divided as follows according to work done:—

(1) Large consumers.
(2) Small consumers.
(3) Prepayment consumers.
(4) Other work.

Each of the above is considered separately and allocated to the three groups.

Statistical Department.

The salaries and wages are divided as follows according to work done:—

(1) Large consumers.
(2) Small consumers.
(3) Other work.

Each of the above is considered separately and allocated to the three groups.

Testing Department.

The total cost of salaries, wages, and materials, is subdivided between:—

(1) Meters for small consumers.
(2) Meters for large consumers.
(3) General testing (*a*) Power stations.
(*b*) High-voltage distribution.

Costs under (3) (*a*) are transferred to generation (repairs and maintenance), and those under (3) (*b*) to high-voltage transmission and distribution (repairs and maintenance). Costs under (1) and (2) are allocated to the three groups in relation to the consumers concerned.

Transport Department.

The costs are kept at the principal garage and are there allocated to departments as they are incurred. When preparing an analysis the amount allocated to any department is arbitrarily divided between any subdivisions of that department in accordance with the use of motor-cars or other transport required by the nature of their duties.

APPENDIX III (1).

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP A.

Item, or proportion of item, allocated to Group A		How this item is expressed in the analysis formula
Working Costs.		
(*a*) *Generation.*		
Fuel	Running proportion	Pence per unit sent out of the power station
Fuel-handling	Running proportion	Pence per unit sent out of the power station
Ash-handling and disposal	Running proportion	Pence per unit sent out of the power station
Steam or waste-heat purchased	Running proportion	Pence per unit sent out of the power station
Current purchased	Running proportion	Pence per unit sent out of the power station
Water	Running proportion	Pence per unit sent out of the power station
Oil and stores	Fixed proportion	£ per kW of demand on the power station
Salaries and wages (operation)	Fixed proportion	£ per kW of demand on the power station
Repairs and maintenance	Fixed proportion	£ per kW of demand on the power station
(*b*) *High-voltage Transmission and Distribution.*		
High-voltage interconnection (operating costs)		£ per kW of demand on the power station
High-voltage interconnection (repairs and maintenance of substation)		£ per kW of demand on the power station
High-voltage interconnection (repairs and maintenance of mains)		£ per kW of demand on the power station
Overhead Costs.		
(*a*) *Management and Departments common to General Business.*		
Management: Proportion corresponding to time devoted to consumers		£ per point of supply
Proportion devoted to other matters		£ per kW of demand on the power station
Secretary's department		£ per kW of demand on the power station
Accountant's department		£ per kW of demand on the power station
Cashier's department		Part £ per point of supply; part £ per kW of demand on the power station
Statistical department		Part £ per point of supply; part £ per kW of demand on the power station
Testing department		Part £ per point of supply; part £ per kW of demand on the power station
Consumers' departments (3) General power supplies		£ per point of supply

APPENDIX III (1)—*continued.*

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP A—*continued.*

Item, or proportion of item, allocated to Group A	How this item is expressed in the analysis formula
(*b*) *Other Costs.*	
Rents, Rates, Taxes, Insurances	£ per kW of demand on the power station
Telephones	Part £ per point of supply; part £ per kW of demand on the power station
Electricity Commissioners' charges	Pence per unit sent out of the power station
Standardization-of-frequency levy	Treated as a special item of cost, calculated as a percentage of the revenue received from the consumers
(*c*) *Miscellaneous Charges.*	
Directors' fees, Stock trustees, Auditors, Legal advisers, Bank charges	£ per kW of demand on the power station
(*d*) *Other Miscellaneous Expenses.*	
Stationery and printing, Stamps and telegrams, Advertising	£ per point of supply
Subscriptions and gratuities, Recreation club, welfare, etc.	£ per kW of demand on the power station

APPENDIX III (2).

METHOD OF ANALYSIS OF CAPITAL EXPENDITURE ALLOCATED TO GROUP A.

Item, or proportion of item, allocated to Group A	How this item is expressed in the analysis formula
Capital Expenditure.	
Generating stations, High-voltage interconnecting mains, High-voltage substations	£ per kW of demand on the power station
Office buildings and equipment	£ per point of supply
Motor vehicles, Test house and equipment, Acts and Orders	£ per kW of demand on the power station

APPENDIX III (3).

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP B.

Item, or proportion of item, allocated to Group B		How this item is expressed in the analysis formula
Working Costs.		
(*a*) *Generation.*		
Fuel, Fuel-handling, Ash-handling and removal, Steam or waste-heat purchased, Current purchased, Water	Running proportion	Pence per unit delivered to consumer's substation
Oil and stores, Salaries and wages (operation), Repairs and maintenance	Fixed proportion	£ per kW of demand on the power station

APPENDIX III (3)—*continued.*

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP B—*continued.*

Item, or proportion of item, allocated to Group B	How this item is expressed in the analysis formula
(*b*) *High-voltage Transmission and Distribution.*	
Salaries and office wages	£ per kW of demand on the power station
High-voltage interconnection (operation costs)	£ per kW of demand on the power station
High-voltage interconnection (repairs and maintenance of substations)	£ per kW of demand on the power station
High-voltage interconnection (repairs and maintenance of mains)	£ per kW of demand on the power station
High-voltage transmission and distribution (operating costs)	Part £ per kW of demand on the power station; part £ per point of supply
High-voltage transmission and distribution (repairs and maintenance of substations)	Part £ per kW of demand on the power station; part £ per point of supply
High-voltage transmission and distribution (repairs and maintenance of mains)	£ per kW of demand on the power station
Overhead Costs.	
(*a*) *Management and Departments common to General Business.*	
Management: Proportion corresponding to time devoted to consumers	£ per point of supply
Proportion devoted to other matters	£ per kW of demand on the power station
Secretary's department	£ per kW of demand on the power station
Accountant's department	£ per kW of demand on the power station
Cashier's department	Part £ per point of supply; part £ per kW of demand on the power station
Statistical department	Part £ per point of supply; part £ per kW of demand on the power station
Testing department	Part £ per point of supply; part £ per kW of demand on the power station
Consumers' departments:—	
(2) Colliery supplies	£ per point of supply to collieries
(3) General power supplies	£ per point of supply to Group B consumers other than collieries
(*b*) *Other Costs.*	
Rents	£ per kW of demand on the power station
Rates	£ per kW of demand on the power station
Taxes	£ per kW of demand on the power station
Insurances (other than National Health, etc.)	£ per kW of demand on the power station
Payments for wayleaves	£ per kW of demand on the power station
Telephones (maintenance and operation of private system)	£ per kW of demand on the power station
Electricity Commissioners' charges	Pence per unit delivered to the consumer's substation (excluding supplies to authorized undertakers)
Standardization-of-frequency levy	Treated as a special item of cost, calculated as a percentage of the revenue received from the consumers (excluding supplies to authorized undertakers)
(*c*) *Miscellaneous Charges.*	
Directors' fees	£ per kW of demand on the power station
Stock trustees	£ per kW of demand on the power station
Auditors	£ per kW of demand on the power station
Legal advisers	£ per kW of demand on the power station
Bank	£ per kW of demand on the power station
(*d*) *Other Miscellaneous Expenses.*	
Stationery and printing	£ per point of supply
Stamps and telegrams	£ per point of supply
Advertising	£ per point of supply
Subscriptions and gratuities	£ per kW of demand on the power station
Recreation club, welfare, etc.	£ per kW of demand on the power station

APPENDIX III (4).

METHOD OF ANALYSIS OF CAPITAL EXPENDITURE ALLOCATED TO GROUP B.

Item, or proportion of item, allocated to Group B	How this item is expressed in the analysis formula
Capital Expenditure.	
Generating stations	£ per kW of demand on the power station
High-voltage interconnecting mains	£ per kW of demand on the power station
High-voltage interconnecting substations	£ per kW of demand on the power station
High-voltage transmission and distribution mains	Part £ per kW of demand on the power station; part £ per point of supply
High-voltage transmission and distribution substations	£ per kW of demand on the power station
Consumers' substations	These are omitted from the analysis formula, and are brought in as definite amounts allocable against certain consumers
Office buildings and equipment	£ per point of supply
Motor vehicles	£ per kW of demand on the power station
Test house and equipment	Part £ per kW of demand on the power station; part £ per point of supply
Acts and Orders	£ per kW of demand on the power station

APPENDIX III (5).

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP C.

Item, or proportion of item, allocated to Group C		How this item is expressed in the analysis formula
Working Costs.		
(*a*) *Generation.*		
Fuel	Running proportion	Pence per unit sold
Fuel-handling	Running proportion	Pence per unit sold
Ash-handling and removal	Running proportion	Pence per unit sold
Steam or waste-heat purchased	Running proportion	Pence per unit sold
Current purchased	Running proportion	Pence per unit sold
Water	Fixed proportion	£ per kVA of " effective demand " at time of heavy high-voltage load
Oil and stores	Fixed proportion	£ per kVA of " effective demand " at time of heavy high-voltage load
Salaries and wages (operation)	Fixed proportion	£ per kVA of " effective demand " at time of heavy high-voltage load
Repairs and maintenance	Fixed proportion	£ per kVA of " effective demand " at time of heavy high-voltage load
(*b*) *High-voltage Transmission and Distribution.*		
Salaries and office wages		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage interconnection (operation costs)		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage interconnection (repairs and maintenance of substations)		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage interconnection (repairs and maintenance of mains)		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage transmission and distribution (operation costs)		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage transmission and distribution (repairs and maintenance of substations)		£ per kVA of " effective demand " at time of heavy high-voltage load
High-voltage transmission and distribution (repairs and maintenance of mains)		£ per kVA of " effective demand " at time of heavy high-voltage load
(*c*) *Low-voltage Distribution.*		
Salaries and office wages		£ per kVA of " effective demand " at time of heavy low-voltage load
Operation of substations		£ per kVA of " effective demand " at time of heavy low-voltage load
Repairs and maintenance of substations		£ per kVA of " effective demand " at time of heavy low-voltage load
Repairs and maintenance of mains		Part £ per kVA of " effective demand " at time of heavy low-voltage load; part £ per consumer, with adjustment between types of low-voltage consumers
Repairs and maintenance of house services		£ per consumer (all network consumers)
Repairs and maintenance of meters		£ per consumer (all network consumers)
Overhead Costs.		
(*a*) *Management and Departments common to General Business.*		
Management:—		
Proportion corresponding to time devoted to consumers		£ per consumer (all network consumers)
Proportion devoted to other matters		£ per kVA of " effective demand " at time of heavy high-voltage load
Secretary's department		£ per kVA of " effective demand " at time of heavy high-voltage load

APPENDIX III (5)—*continued.*

METHOD OF ANALYSIS OF COSTS ALLOCATED TO GROUP C—*continued.*

Item, or proportion of item, allocated to Group C	How this item is expressed in the analysis formula
Overhead Costs—continued.	
(*a*) *Management and Departments common to General Business—continued.*	
Accountant's department	Part £ per consumer (excluding prepayment consumers); part £ per kVA of "effective demand" at time of heavy high-voltage load
Cashier's department	Part £ per consumer (all quarterly network consumers); part £ per consumer (prepayment consumers only); part £ per kVA of "effective demand" at time of heavy high-voltage load
Statistical department	Part £ per consumer (excluding prepayment consumers); part £ per kVA of "effective demand" at time of heavy high-voltage load
Testing department	Part £ per consumer (all network consumers); part £ per kVA of "effective demand" at time of heavy low-voltage load
Consumers' departments:—	
(1) Lighting and domestic	£ per consumer (all lighting and domestic consumers)
(2) General power supplies	£ per consumer (power consumers supplied from low-voltage networks only)
Showrooms and branch offices	£ per consumer (all lighting and domestic, reduced amount for prepayment consumers)
(*b*) *Other Costs.*	
Rents	£ per kVA of "effective demand" at time of heavy high-voltage load
Rates	£ per kVA of "effective demand" at time of heavy low-voltage load
Taxes	£ per kVA of "effective demand" at time of heavy high-voltage load
Insurances (other than National Health, etc.)	
Payments for wayleaves	
Telephones (maintenance and operation of private system)	Part £ per kVA of "effective demand" at time of heavy low-voltage load; part £ per consumer
Electricity Commissioners' charges	Pence per unit sold
Standardization-of-frequency levy	Treated as a special item of cost, calculated as a percentage of the revenue received from consumers
(*c*) *Miscellaneous Charges.*	
Directors' fees	£ per kVA of "effective demand" at time of heavy low-voltage load
Stock trustees	
Auditors	
Legal advisers	
Bank	
(*d*) *Other Miscellaneous Expenses.*	
Stationery and printing	£ per consumer (reduced proportion to prepayment consumers)
Stamps and telegrams	
Advertising	
Subscriptions and gratuities	£ per kVA of "effective demand" at time of heavy low-voltage load
Recreation club, welfare, etc.	£ per kVA of "effective demand" at time of heavy high-voltage load

APPENDIX III (6).

METHOD OF ANALYSIS OF CAPITAL EXPENDITURE ALLOCATED TO GROUP C.

Item, or proportion of item, allocated to Group C	How this item is expressed in the analysis formula
Capital Expenditure.	
Generating stations	£ per kVA of "effective demand" at time of heavy high-voltage load
High-voltage interconnecting mains	
High-voltage interconnecting substations	
High-voltage transmission and distribution mains	
High-voltage transmission and distribution sub-stations	
Low-voltage distribution mains	* Part £ per kVA of "effective demand" at time of heavy low-voltage load; part £ per "standard domestic" consumer

* See note on following page.

APPENDIX III (6)—*continued.*

METHOD OF ANALYSIS OF CAPITAL EXPENDITURE ALLOCATED TO GROUP C—*continued.*

Item, or proportion of item, allocated to Group C	How this item is expressed in the analysis formula
Low-voltage distribution substations	£ per kVA of " effective demand " at time of heavy low-voltage load
House services	This item is not included as a factor of the formula, but an amount depending on the conditions of the supply is added
Meters (other than those in power stations or sub-stations)	In a similar manner to house services
Office buildings and equipment	£ per " standard domestic " consumer
Motor vehicles	Part £ per " standard domestic " consumer; part £ per kVA of " effective demand " at time of heavy low-voltage load
Test house and equipment	Part £ per " standard domestic " consumer; part £ per kVA of " effective demand " at time of heavy low-voltage load
Acts and Orders	£ per kVA of " effective demand " at time of heavy low-voltage load

* It is a simple matter to allocate both the capital cost of mains and their maintenance to consumers on the basis of the demands made by the consumers. Investigation into the capital cost of mains, however, soon shows such a simple and direct method to be incorrect: this is due to the fact that the cost of a given length of cable does not vary directly with the load which it will carry; a cable to carry 200 kVA will cost much less than double the cost of a cable for 100 kVA. This is further accentuated by the fact that the cost of opening-up the streets and of reinstatement is the same whatever the size of cable to be laid. In the same way, the maintenance of a cable is as much due to the presence of the cable as to the load that it carries.

It having been decided to analyse a large proportion of the low-voltage mains on a consumer basis, it was realized that to allocate similar amounts to all network consumers, whether shops, offices, large houses, or terrace flats, would be obviously unfair.

The following basis was arrived at; it has the merit that it requires for its use only the data that are usually available and strikes a compromise between simplicity and accuracy. It was found that for houses and flats the street frontage is roughly proportional to the lighting installation. The average house having a lighting installation of 470 watts was called the " standard domestic " consumer, small shops were averaged at $1\frac{1}{2}$ " standard domestic " consumers, and small power consumers at 2 " standard domestic " consumers.

APPENDIX IV.

COST ANALYSIS FOR YEAR ENDING 31ST DECEMBER, 1931.

Technical Data for Allocation of Costs between Groups of Consumers and for Analysis of Allocated Costs.

Units sent out of power stations	170 300 000
Units purchased	31 200 000
Total units	201 500 000
Demand met by undertaker's own power stations	45 500 kW
Demand met by current purchased	9 000 kW
	54 500 kW
Average monthly load factor of power stations, 51·3 per cent.	

Group A. Consumers supplied at power-station busbars.

Number of consumers	4
Demand on power station	4 800 kW
Units at power station	34 000 000

Group B. Consumers supplied from high-voltage distribution system.

Number of points of supply	70
Demand on power station	34 500 kW
High-voltage units delivered at substations of Group B consumers	134 250 000

Group C. Consumers supplied from low-voltage networks.

Number of Consumers (allowance being made for consumers only connected a short time).

Number of prepayment consumers	17 400
Number of quarterly consumers (shops, offices, etc.)	2 000
Number of houses	16 520
Number of small-motor consumers	1 300
Total	37 220
Effective demand at consumers' terminals at time of heavy high-voltage load	16 500 kVA
Effective demand at time of heavy low-voltage load	18 100 kVA
Units sold to Group C consumers	20 101 000

Special Consumer basis for analysis of low-voltage mains item.†

The average domestic consumer is taken as a standard.

Number of domestic consumers	33 920
Shops, offices, etc., 2 000 × $1\frac{1}{2}$	3 000
Small-motor consumers, 1 300 × 2	2 600
" Standard consumers "	39 520
Number of consumers (excluding prepayment)	19 820
Number of consumers (excluding small motors)	35 920

Percentages of Units Sent Out of Power Stations.

Group	Units into system for group	Percentage of total units into system
	kWh	per cent
A	34 000 000	16·87
B	143 000 000	70·98
C	24 500 000	12·15
Total	201 500 000	100·00

Percentages of Demands on Power Stations.

Group	Demand on power station due to group	Percentage of total demand on power station
	kW	per cent
A	4 800	8·80
B	34 500	63·33
C	15 200	27·87
Total	54 500	100·00

† See footnote to Appendix III.

ALLOCATION OF ANNUAL COSTS BETWEEN THE THREE GROUPS OF CONSUMERS.

Items of cost	Per cent of total	Amount	Group A		Group B		Group C	
Working Costs.								
(*a*) *Generation.*								
Running Proportions.								
	per cent	£	per cent	£	per cent	£	per cent	£
Fuel	86·78	80 500	16·87	13 580	70·98	57 141	12·15	9 780
Fuel-handling	86·78	2 256	16·87	381	70·98	1 601	12·15	274
Ash-handling and disposal	86·78	3 254	16·87	549	70·98	2 310	12·15	395
Current purchased	68·00	44 200	16·87	7 455	70·98	31 373	12·15	5 370
Water	83·22	441	16·87	74	70·98	313	12·15	54
Oil and stores	83·22	1 331	16·87	224	70·98	945	12·15	162
Salaries and wages	16·30	3 447	16·87	581	70·98	2 447	12·15	419
Repairs and maintenance	31·00	6 730	16·87	1 136	70·98	4 777	12·15	818
Total	—	£142 159	—	£23 980	—	£100 907	—	£17 272
Fixed Proportions.								
Fuel	13·22	12 250	8·80	1 078	63·33	7 758	27·87	3 414
Fuel-handling	13·22	344	8·80	30	63·33	218	27·87	96
Ash-handling and disposal	13·22	496	8·80	44	63·33	314	27·87	138
Current purchased	32·00	20 800	8·80	1 830	63·33	13 171	27·87	5 799
Water	16·78	89	8·80	8	63·33	56	27·87	25
Oil and stores	16·78	269	8·80	24	63·33	170	27·87	75
Salaries and wages	83·70	17 703	8·80	1 558	63·33	11 211	27·87	4 934
Repairs and maintenance	69·00	14 990	8·80	1 319	63·33	9 494	27·87	4 177
Total	—	£66 941	—	£5 891	—	£42 392	—	£18 658
Total Generation Costs (Running and Fixed)	—	£209 100	—	£29 871	—	£143 299	—	£35 930
(*b*) *High-voltage Transmission and Distribution.*								
Salaries and office wages		3 520	1·0	35	74·0	2 605	25·0	880
Interconnection (Operation)		220	8·80	19	63·33	139	27·87	62
(Repairs and maintenance of substations)		200	8·80	17	63·33	127	27·87	56
(mains)		650	8·80	57	63·33	412	27·87	181
Transmission (Operation)		3 300	—	—	75·0	2 475	25·0	825
(Repairs and maintenance of substations)		2 100	—	—	75·0	1 575	25·0	525
(mains)		5 100	—	—	75·0	4 075	25·0	1 025
Total High-voltage Transmission and Distribution		£15 090	—	£128	—	£11 408	—	£3 554
(*c*) *Low-voltage Distribution.*								
Salaries and office wages		10 250	—	—	—	—	100·0	10 250
Operation of substations		9 320	—	—	—	—	100·0	9 320
Repairs and maintenance of substations		1 750	—	—	—	—	100·0	1 750
mains		12 200	—	—	—	—	100·0	12 200
house services		1 100	—	—	—	—	100·0	1 100
meters		1 800	—	—	—	—	100·0	1 800
Total Low-voltage Distribution		£36 420	—	—	—	—	—	£36 420

Overhead Costs.							
(*a*) *Management and Departments common to General Business.*							
Management:—Proportion for consumers	1 630	3	49	57	929	40	652
other matters	1 180	4	47	46	543	50	590
Secretary's department	1 200	4	48	46	552	50	600
Accountant's department:—Proportion for consumers	2 300	—	20	15	345	85	1 935
other matters	1 520	4	61	46	699	50	760
Cashier's department:—Proportion for prepayment consumers	1 200	—	—	—	—	100	1 200
other consumers	2 700	—	12	8	216	92	2 472
other matters	1 520	4	61	46	699	50	760
Statistical department:—Proportion for consumers	3 100	—	—	10	310	90	2 790
other matters	700	4	28	46	322	50	350
Testing department:—Special allocation	1 795	—	25	—	70	—	1 700
Transport department (Divided among appropriate items)	—	—	—	—	—	—	—
Consumers' departments: (1) Lighting and domestic	6 920	—	—	—	—	100	6 920
(2) Colliery supplies	910	—	—	100	910	—	—
(3) General power supplies	1 400	10	140	60	840	30	420
Showrooms and branch offices	1 280	—	—	—	—	100	1 280
(*b*) *Other Costs.*							
Rents	2 310	5	116	60	1 386	35	808
Rates	28 365	4	1 216	46	13 419	50	13 730
Taxes	3 880	4	155	46	1 785	50	1 940
Insurances	2 150	4	86	46	989	50	1 075
Wayleaves	2 300	1	23	60	1 380	39	897
Telephones (Maintenance and operation)	1 100	5	55	60	660	35	385
Electricity Commissioners' charges	1 000	17	170	71	710	12	120
Standardization-of-frequency levy	3 000	6	180	54	1 620	40	1 200
(*c*) *Miscellaneous Charges.*							
Directors' fees	600	4	24	46	276	50	300
Stock trustees	500	4	20	46	230	50	250
Auditors	250	6	15	54	135	40	100
Legal advisers	800	2	16	38	304	60	480
Bank	50	4	2	46	23	50	25
(*d*) *Other Miscellaneous Expenses.*							
Stationery and printing	1 000	—	11	20	200	80	789
Stamps and telegrams	500	—	6	20	100	80	394
Advertising	1 600	—	16	18	288	82	1 296
Subscriptions and gratuities	700	6	42	54	378	40	280
Recreation club, welfare, etc.	150	6	9	54	81	40	60
Total Costs other than Generation and Distribution	£79 610	—	£2 653	—	£30 399	—	£46 558
Total Costs for Calendar Year	£340 220	—	£32 652	—	£185 106	—	£122 462

ALLOCATION OF CAPITAL EXPENDITURE BETWEEN THE THREE GROUPS OF CONSUMERS.

Generating stations	1 110 000	8·80	97 680	63·33	702 963	27·87	309 357
High-voltage interconnecting substations	20 000	8·80	1 760	63·33	12 666	27·87	5 574
mains	30 000	8·80	2 640	63·33	18 999	27·87	8 361
High-voltage transmission and distribution substations	110 000	—	—	75·00	82 500	25·00	27 500
mains	500 000	—	—	75·00	375 000	25·00	125 000
Low-voltage distribution mains (allocated on kW basis)	180 000	—	—	—	—	100·00	180 000
(consumer basis)	275 000	—	—	—	—	100·00	275 000
Low-voltage distribution substations	150 000	—	—	—	—	100·00	150 000
House services	140 000	—	—	—	—	100·00	140 000
Meters (other than those in power stations and substations)	70 000	—	—	—	—	100·00	70 000
Office buildings and equipment (allocated on kW basis)	15 000	20·00	3 000	30·00	4 500	50·00	7 500
(consumer basis)	26 000	0·20	292	19·80	5 148	80·00	20 560
Motor vehicles	15 000	1·00	150	39·00	5 850	60·00	9 000
Test house and equipment:—General	2 000	1·00	20	74·00	1 480	25·00	500
Meter testing	7 000	0·20	14	39·80	2 786	60·00	4 200
Acts and Orders	25 000	2·00	500	38·00	9 500	60·00	15 000
Total Capital Expenditure to Date	£2 675 000	—	£106 056	—	£1 221 392	—	£1 347 552

ANALYSIS OF COSTS. GROUP A CONSUMERS.

Items of cost	Amount	Cost per unit sent out of power station	Cost per kW at power station	Cost per point of supply
Working Costs.				
(*a*) *Generation.*				
Running Proportions.	£	d.	£	£
Fuel	13 580	0·09586	—	—
Fuel-handling	381	0·00269	—	—
Ash-handling and disposal	549	0·00388	—	—
Current purchased	7 455	0·05262	—	—
Water	74	0·00052	—	—
Oil and stores	224	0·00158	—	—
Salaries and wages	581	0·00410	—	—
Repairs and maintenance	1 136	0·00802	—	—
Total	£23 980	0·16927d.	—	—
Fixed Proportions.				
Fuel	1 078	—	0·2245	—
Fuel-handling	30	—	0·0062	—
Ash-handling and disposal	44	—	0·0092	—
Current purchased	1 830	—	0·3810	—
Water	8	—	0·0017	—
Oil and stores	24	—	0·0050	—
Salaries and wages	1 558	—	0·3248	—
Repairs and maintenance	1 319	—	0·2750	—
Total	£5 891	—	£1·2274	—
Total Generation Costs (Running and Fixed)	£29 871	0·16927d.	£1·2274	—
(*b*) *High-voltage Transmission and Distribution.*				
Salaries and office wages	35	—	0·0073	—
Interconnection:—Operation	19	—	0·0039	—
Repairs and maintenance of substations	17	—	0·0035	—
mains	57	—	0·0119	—
Total Interconnection Costs	£128	—	£0·0266	—
Overhead Costs.				
(*a*) *Management and Departments common to General Business.*				
Management:—Proportion for consumers	49	—	—	12·25
other matters	47	—	0·0098	—
Secretary's department	48	—	0·0100	—
Accountant's department:—Proportion for consumers	20	—	—	5·00
other matters	61	—	0·0127	—
Cashier's department:—Proportion for consumers	12	—	—	3·00
other matters	61	—	0·0127	—

Statistical department:—Proportion for consumers	10	—	—	2·50
other matters	18	—	0·0037	—
Testing department:—Meter testing	25	—	0·0052	—
Consumers' department:—(*c*) General power supplies	140	—	—	35·00
(*b*) *Other Costs.*				
Rents	116	—	0·0242	—
Rates	1 216	—	0·2533	—
Taxes	155	—	0·0323	—
Insurances	86	—	0·0179	—
Wayleaves	23	—	0·0048	—
Telephones	55	—	0·0115	—
Electricity Commissioners' charges	170	0·00120d.	—	—
Standardization-of-frequency levy	180	(Charge on revenue)	—	—
(*c*) *Miscellaneous Charges.*				
Directors' fees	24	—	0·0050	—
Stock trustees	20	—	0·0042	—
Auditors	15	—	0·0031	—
Legal advisers	16	—	0·0033	—
Bank	2	—	0·0004	—
(*d*) *Other Miscellaneous Expenses.*				
Stationery and printing	11	—	—	2·75
Stamps and telegrams	6	—	—	1·50
Advertising	16	—	—	4·00
Subscriptions and gratuities	42	—	0·0087	—
Recreation club, welfare, etc.	9	—	0·0019	—
Total Costs other than Generation and Distribution	£2 653	0·00120d.	£0·4247	£66·00
Total Costs allocated to Group A	£32 652	0·17047d.	£1·6787	£66·00

ANALYSIS OF CAPITAL, GROUP A.

Item of capital expenditure	Amount	Capital per kW of demand	Capital per point of supply
	£	£	£
Generating stations	97 680	20·350	—
High-voltage interconnection (substations)	1 760	0·367	—
(mains)	2 640	0·550	—
Office buildings and equipment (kW basis)	3 000	0·625	—
(consumer basis)	292	—	73·0
Motor vehicles	150	0·031	—
Test house and equipment (General)	20	0·004	—
(Meter testing)	14	0·003	—
Acts and Orders	500	0·104	—
Total Capital allocated to Group A Consumers	£106 056	£22·034	£73·0

ANALYSIS OF COSTS. GROUP B.

Items of cost	Amount	Cost per unit to consumers' substations	Cost per kW at power station	Cost per point of supply
Working Costs.				
(*a*) *Generation Costs.*				
Running Proportions.	£	d.	£	£
Fuel	57 141	0·10215	—	—
Fuel-handling	1 601	0·00286	—	—
Ash-handling	2 310	0·00413	—	—
Current purchased	31 373	0·05609	—	—
Water	313	0·00056	—	—
Oil and stores	945	0·00169	—	—
Salaries and wages	2 447	0·00437	—	—
Repairs and maintenance	4 777	0·00854	—	—
Total	£100 907	0·18039d.	—	—
Fixed Proportions.				
Fuel	7 758	—	0·22487	—
Fuel-handling	218	—	0·00632	—
Ash-handling	314	—	0·00910	—
Current purchased	13 171	—	0·38177	—
Water	56	—	0·00162	—
Oil and stores	170	—	0·00493	—
Salaries and wages	11 211	—	0·32496	—
Repairs and maintenance	9 494	—	0·27519	—
Total	£42 392	—	£1·22876	—
Total Generation Costs (Running and Fixed)	£143 299	0·18039d.	£1·22876	—
(*b*) *High-voltage Transmission and Distribution.*				
Salaries and office wages	2 605	—	0·07551	—
Interconnection (Operation)	139	—	0·00403	—
(Repairs and maintenance of substations)	127	—	0·00368	—
(mains)	412	—	0·01194	—
Transmission (Operation)	1 100	—	—	15·714
	1 375	—	0·03986	—
(Repairs and maintenance of substations)	500	—	—	7·143
	1 075	—	0·03116	—
(mains)	4 075	—	0·11812	—
Total High-voltage Transmission and Distribution	£11 408	—	£0·28430	£22·857
Overhead Costs.				
(*a*) *Management and Departments common to General Business.*				
Management:—Proportion for consumers	929	—	—	13·271
other matters	543	—	0·01574	—
Secretary's department	552	—	0·01600	—
Accountant's department:—Proportion for consumers	345	—	—	4·928
other matters	699	—	0·02026	—

Cashier's department:—Proportion for consumers	216	—	—	3·086
other matters	699	—	0·02026	—
Statistical department:—Proportion for consumers	310	—	—	4·429
other matters	322	—	0·00933	—
Testing department	70	—	—	1·000
Consumers' department:—(2) Colliery supplies	910	—	—	25·000
(3) General power supplies	840	—	—	
(*b*) *Other Costs.*				
Rents	1 386	—	0·04017	—
Rates	13 419	—	0·38896	—
Taxes	1 785	—	0·05174	—
Insurances	989	—	0·02867	—
Wayleaves	1 380	—	0·04000	—
Telephones (maintenance and operation)	60	—	—	0·857
	600	—	0·01739	—
Electricity Commissioners' charges	710	0·00127d.	—	—
Standardization-of-frequency levy	1 620	(charge on revenue)	—	—
(*c*) *Miscellaneous Charges.*				
Directors' fees	276	—	0·00800	—
Stock trustees	230	—	0·00666	—
Auditors	135	—	0·00391	—
Legal advisers	304	—	0·00881	—
Bank	23	—	0·00067	—
(*d*) *Other Miscellaneous Expenses.*				
Stationery and printing	200	—	—	2·857
Stamps and telegrams	100	—	—	1·428
Advertising	288	—	—	4·114
Subscriptions and gratuities	378	—	0·01096	—
Recreation club, welfare, etc.	81	—	0·00235	—
Total Costs other than Generation and Distribution	£30 399	0·00127d.	£0·68988	£60·970
Total Costs allocated to Group B	£185 106	0·18166d.	£2·20294	£83·827

ANALYSIS OF CAPITAL. GROUP B.

Item of capital expenditure	Amount	Capital per kW of demand on the power stations	Capital per point of supply
	£	£	£
Generating stations	702 963	20·3700	—
High-voltage interconnecting substations	12 666	0·3670	—
mains	18 999	0·5505	—
High-voltage transmission and distribution substations	82 500	2·3910	—
mains (consumer basis)	70 000	—	1 000·00
mains (kW basis)	305 000	8·8400	—
Office buildings and equipment (kW basis)	4 500	0·1304	—
(consumers' basis)	5 148	—	73·54
Motor vehicles	5 850	0·1695	—
Test house and equipment (general testing)	1 480	0·0429	—
(meter testing)	2 786	—	39·80
Acts and Orders	9 500	0·2755	—
Total Capital Expenditure allocated to Group B	£1 221 392	£33·1368	£1 113·34

ANALYSIS OF COSTS. GROUP C.

Items of cost	Amount	Cost per unit sold	Cost per kVA of effective demand		Cost per consumer involved
			At time of heavy high-voltage loads	At time of heavy low-voltage loads	
Working Costs.					
(*a*) *Generation.*					
Running Proportions.	£	d.	£	£	£
Fuel	9 780	0·11680	—	—	—
Fuel-handling	274	0·00327	—	—	—
Ash-handling	395	0·00472	—	—	—
Current purchased	5 370	0·06415	—	—	—
Water	54	0·00065	—	—	—
Oil and stores	162	0·00193	—	—	—
Salaries and wages	419	0·00505	—	—	—
Repairs and maintenance	818	0·00977	—	—	—
Total	£17 272	0·20634d.	—	—	—
Fixed Proportions.					
Fuel	3 414	—	0·2070	—	—
Fuel-handling	96	—	0·0058	—	—
Ash-handling	138	—	0·0084	—	—
Current purchased	5 799	—	0·3515	—	—
Water	25	—	0·0015	—	—
Oil and stores	75	—	0·0045	—	—
Salaries and wages	4 934	—	0·2991	—	—
Repairs and maintenance	4 177	—	0·2531	—	—
Total	£18 658	—	£1·1309	—	—
Total Generation Costs (Running and Fixed)	£35 930	0·20634d.	£1·1309	—	—
(*b*) *High-voltage Transmission and Distribution.*					
Salaries and office wages	880	—	0·0533	—	—
Interconnection (Operation)	62	—	0·0038	—	—
(Repairs and maintenance of substations)	56	—	0·0034	—	—
(mains)	181	—	0·0110	—	—
Transmission (Operation)	825	—	0·0500	—	—
(Repairs and maintenance of substations)	525	—	0·0318	—	—
(mains)	1 025	—	0·0621	—	—
Total High-voltage Transmission and Distribution	£3 554	—	£0·2154	—	—
(*c*) *Low-voltage Distribution.*					
Salaries and office wages	10 250	—	—	0·5662	—
Operation of substations	9 320	—	—	0·5150	—
Repairs and maintenance of substations	1 750	—	—	0·0967	—
mains (consumer basis)	7 200	—	—	—	0·1822
mains (kVA basis)	5 000	—	—	0·2764	—
house services	1 100	—	—	—	0·0296
meters	1 800	—	—	—	0·0484
Total Low-voltage Distribution	£36 420	—	—	£1·4543	—

Overhead Costs.					
(*a*) *Management and Departments common to General Business.*					
Management:—Proportion for consumers	652	—	—	—	0·1750
other matters	590	—	0·0358	—	—
Secretary's department	600	—	0·0364	—	—
Accountant's department:—Proportion for consumers	1 935	—	—	—	0·0977
other matters	760	—	0·0460	—	—
Cashier's department:—Proportion for prepayment consumers	1 200	—	—	—	0·0690
other consumers	2 472	—	—	—	0·1247
other matters	760	—	0·0460	—	—
Statistical department:—Proportion for consumers	2 790	—	—	—	0·1407
other matters	350	—	0·0212	—	—
Testing department (consumer basis)	1 700	—	—	—	0·0457
Consumers' departments: (1) Lighting and domestic	6 920	—	—	—	0·1928
(3) Power supplies	420	—	—	—	0·3230
Showrooms and branch offices	1 280	—	—	—	0·0357
(*b*) *Other Costs.*					
Rents	808	—	0·0490	—	—
Rates	13 730	—	—	0·7586	—
Taxes	1 940	—	0·1176	—	—
Insurances	1 075	—	0·0652	—	—
Wayleaves	897	—	0·0544	—	—
Telephones (maintenance and operation)	385	—	—	0·2130	—
Electricity Commissioners' charges	120	0·00143d.	—	—	—
Standardization-of-frequency levy	1 200	(revenue basis)	—	—	—
(*c*) *Miscellaneous Charges.*					
Directors' fees	300	—	—	0·0166	—
Stock trustees	250	—	—	0·0138	—
Auditors	100	—	—	0·0053	—
Legal advisers	480	—	—	0·0265	—
Bank	25	—	—	0·0014	—
(*d*) *Other Miscellaneous Expenses.*					
Stationery and printing	789	—	—	—	0·0366
Stamps and telegrams	394	—	—	—	0·0183
Advertising	1 296	—	—	—	0·0601
Subscriptions and gratuities	280	—	—	0·0155	—
Recreation clubs, welfare, etc.	60	—	0·0036	—	—
Total Costs other than Generation and Distribution	£46 558	0·00143d.	£0·4752	£0·8592	—
Total Costs allocated to Group C	£122 462	0·20777d.	£1·8215	£2·3135	See summary of Group C consumer costs

ANALYSIS OF CAPITAL. GROUP C.

Item of capital expenditure	Amount	Capital per kVA of effective demand		Capital per "standard domestic" consumer
		At time of heavy high-voltage loads	At time of heavy low-voltage loads	
	£	£	£	£
Generating stations	309 357	18·750	—	—
High-voltage interconnecting substations	5 574	0·338	—	—
mains	8 361	0·507	—	—
High-voltage transmission and distribution (substations)	27 500	1·666	—	—
(mains)	125 000	7·575	—	—
Low-voltage distribution mains (allocation on kVA basis)	180 000	—	9·950	—
(allocation on consumer basis)	275 000	—	—	6·960
substation	150 000	—	8·288	—
House services	140 000	—	—	—
Meters (other than those in power stations and substations)	70 000	—	—	—
Office buildings and equipment allocated on kVA basis	7 500	—	0·414	—
on consumer basis	20 800	—	—	0·527
Motor vehicles (consumer basis)	5 000	—	—	0·127
(kVA basis)	4 000	—	0·221	—
Test house and equipment (general)	500	—	0·028	—
(meter testing)	4 200	—	—	0·106
Acts and Orders	15 000	—	0·829	—
Total Capital Expenditure allocated to Group C	£1 347 792	£28·836	£19·730	£7·720

Summary of Group C Consumer Costs.

Items	Prepayment consumers	Small-motor consumers	Quarterly domestic consumers	Quarterly shops, offices, etc.
	£	£	£	£
Low-voltage Distribution.				
Repairs and maintenance of mains	0·1822	0·3644*	0·1822	0·2733†
house services	0·0296	0·0296	0·0296	0·0296
meters	0·0484	0·0484	0·0484	0·0484
Distribution consumer costs	£0·2602	£0·4424	£0·2602	£0·3513
Management, etc.				
Management	0·0175	0·0175	0·0175	0·0175
Accountancy	—	0·0977	0·0977	0·0977
Cashiers (Prepayment consumers)	0·0690	—	—	—
(Other consumers)	—	0·1247	0·1247	0·1247
Statistical (exclude prepayment)	—	0·1407	0·1407	0·1407
Testing department	0·0457	0·0457	0·0457	0·0457
Lighting department	0·1928	—	0·1928	0·1928
Power department	—	0·3230	—	—
Showroom	0·0357	—	0·0357	0·0357
Stationery and printing	0·0037‡	0·0366	0·0366	0·0366
Stamps and telegrams	0·0018‡	0·0183	0·0183	0·0183
Advertising	0·0060‡	0·0601	0·0601	0·0601
Management, etc., consumer costs	£0·3722	£0·8643	£0·7698	£0·7698
Total Consumer Costs	£0·6324	£1·3067	£1·0300	£1·1211

* 0·1822 × 2 (see footnote to Appendix III).
† 0·1822 × 1·5 (see footnote to Appendix III).
‡ A prepayment consumer is assumed to involve one-tenth the cost of one quarterly consumer in respect of these items.

Formulæ Derived from Analysis Given on Pages 872–878.

Group A Consumers.

Costs per annum.

(1) Per kW of demand made on the power stations .. .. £1·679
(2) Per point of supply .. .. .. £66·00
(3) Per unit sent out of the power stations .. .. 0·1705d.

Capital.

(4) Per kW of demand made on the power stations .. .. £22·03
(5) Per point of supply .. .. .. £73·0

Group B Consumers.

Costs per annum.

(1) Per kW of demand made on the power stations .. .. £2·203
(2) Per point of supply .. .. .. £83·8
(3) Per unit delivered to the high-voltage busbars at the substation .. .. 0·1817d.

Capital.

(4) Per kW of demand made on the power stations .. .. £33·14
(5) Per point of supply .. .. .. £113·3
(6) Special capital (to be allocated according to circumstances). Average per point of supply £1 000

Group C Consumers.

Costs per annum.

(1) Per kVA of "effective demand" occurring during the period of heavy load on the high-voltage system and power stations .. .. .. £1·82
(2) Per kVA of "effective demand" occurring during the period of heavy load on low-voltage networks .. £2·314
(3) Per unit sold .. .. 0·208d.
(4) Per consumer:—
(*a*) Domestic (quarterly accounts) .. £1·03
(*b*) Shops, offices, etc. .. .. .. £1·12
(*c*) Domestic (prepayment) .. .. £0·63
(*d*) Industrial power consumers .. £1·31

Capital.

(5) Per kVA of "effective demand" occurring during period of heavy load on the high-voltage system and power stations .. .. .. £28·84

(6) Per kVA of "effective demand" occurring during the period of heavy load on the low-voltage networks:—

(*a*) For use when considering existing supplies .. .. £19·73

(*b*) For use when considering supplies involving low-voltage network extensions .. .. £9·78

(*c*) For use when considering supplies involving expenditure on a complete network, including a new substation .. .. £1·49

(7) Per consumer, as follows:—

Type of consumer	Factor (£ per consumer) to be used for	
	Supplies from existing mains	Supplies involving expenditure on mains
	£	£
(*a*) Standard domestic ..	7·72	0·76
(*b*) Shop, office, etc. ..	11·58	1·14
(*c*) Small works	15·44	1·52

APPENDIX V.

Data for Consumers Supplied from Low-voltage Networks.

The figures tabulated consist chiefly of statistics as to the annual consumption and demands of various types of consumers. The consumption figures have been accumulated over a period of years; the demands have in most cases been obtained by load curves such as those given in the paper and discussed in Appendix VI, and the figures given as effective demand on the high-voltage

Table 4.

Residential Consumers Taking a Supply for Lighting only, with a Proportion using Irons through the same Meter.

Size of house, based on assessable rooms*	Size of lighting installation	Annual consumption	Effective demand	
			On high-voltage system	On low-voltage network
rooms	watts	kWh	kVA	kVA
3	150	80	0·025	0·050
4	250	100	0·030	0·060
5	400	130	0·037	0·074
6	550	170	0·047	0·094
7	700	220	0·058	0·116
8	900	280	0·071	0·142
9	1 050	350	0·088	0·176
10	1 200	420	0·104	0·208
11	1 400	490	0·111	0·222
12	1 600	560	0·140	0·280
13	1 800	630	0·157	0·314
14	2 000	700	0·175	0·350
15	2 200	775	0·195	0·390

* In counting the assessable rooms, the following are omitted: scullery, bathroom, lavatory, unfurnished attics, and landings.

Table 5.

Domestic Consumers Supplied through Prepayment Meters and Taking a Supply for Lighting only.

Number of lights in installation	Annual consumption	Effective demand	
		On high-voltage system	On low-voltage network
	kWh	kVA	kVA
1	62	0·018	0·036
2	70	0·020	0·041
3	78	0·023	0·046
4	85	0·025	0·050
5	92	0·027	0·054
6	100	0·029	0·058
7	108	0·032	0·063
8 and over	115	0·034	0·067

Table 6.

Domestic Consumers Taking a Supply for Heating, Cooking, and Small Appliances, as well as Lighting.

Brief description of conditions	Total connected load	Annual consumption	Effective demand	
			On high-voltage system	On low-voltage network
	kW	kWh	kVA	kVA
Small house in Council Housing Scheme with full electrical equipment but one multi-purpose coal fire	15·5	900	0·18	0·35
Medium size, with small appliances	2·1	750	0·20	0·37
Medium size, with electric heating and cooking installed but not used exclusively	13·2	2 200	0·40	0·65
Small house with full electrical equipment and liberal use	20·7	9 500	1·80	2·50

system and low-voltage system respectively relate to load conditions on the system of the Newcastle-upon-Tyne Electric Supply Co. and its subsidiary companies.

TABLE 7.

Miscellaneous Lighting Consumers.

Premises supplied	Annual consumption per kW of lighting connected	Effective demand	
		On high-voltage system	On low-voltage network
	kWh	kVA	kVA
Offices	320	0·800	0·800
Banks	450	0·800	0·800
Workrooms	500	0·720	0·720
Small works	350	0·500	0·500
Garages: Public	1 160	0·750	0·750
Private ..	140	0·100	0·100
Schools up to 5 kW ..	200	0·500	0·500
Cafés and restaurants ..	700	0·720	0·720
Public houses	800	0·100	0·600
Social clubs	1 500	0·300	0·500
Churches	215	—	0·200

TABLE 8.

Small Power Consumers Supplied from Low-voltage Networks.

Premises supplied	Consumption per kW of power connected	Effective demand	
		On high-voltage system	On low-voltage network
	kWh	kVA	kVA
Bakers (small)	545	0·150	0·165
Boot repairers	400	0·410	0·410
Builders' yard (excluding mortar mill)	200	0·130	0·115
Builders' yard (mortar mill only)	800	0·400	0·400
Butchers up to 1 h.p. connected	200	0·080	0·070
Butchers over 1 h.p. ..	570	0·200	0·200
Cabinet makers	385	0·200	0·190
Confectionery works ..	800	0·500	0·400
Engineers (manufacturing) ..	350	0·230	0·250
Grocer's shop (small machines, etc.)	200	0·150	0·100
Hoists (friction)	80	0·050	0·050
Hoists (goods)	180	0·100	0·100
Hoists (passenger)	270	0·200	0·200
Laundries	1 000	0·550	0·550
Millers	490	0·200	0·200
Motor garages	300	0·150	0·150
Printers	490	0·270	0·260
Saw mills	495	0·220	0·200
Welders	290	0·170	0·160

In those cases where the consumption is tabulated side by side with size of installation, special care has been taken not to compare recent consumptions with figures of connections which may have become out of date.

It is not suggested that all the figures are of equal accuracy, as the facilities for investigation differ, and naturally the time which can be devoted to the study of a particular class of consumer depends on the relative importance of that class from the point of view of electricity supply.

Houses and shops form a large and important section of consumers and it was soon realized that accurate information with regard to these consumers was essential for development on the right lines. Special attention has therefore been devoted to them, but more work remains to be done with regard to houses making an extended use of electricity.

TABLE 9.

Shops Graded according to Size of Lighting Installations.

Size of installation	Estimated annual consumption	Effective demand for both high-voltage system and low-voltage network
watts	kWh	kVA
100	80	0·080
200	160	0·160
300	215	0·240
400	270	0·320
500	315	0·400
600	360	0·480
700	400	0·560
800	440	0·640
900	475	0·720
1 000	510	0·800
1 200	580	0·950
1 400	650	1·100
1 600	710	1·240
1 800	770	1·370
2 000 and over	410 per kW installed	0·750 per kW installed

An examination of the data for houses and shops will show that the lighting consumptions and demands are not directly proportional to the connections, although in houses of all sizes the effective demand on the low-voltage system appears to be just double that on the high-voltage system.

In the case of the miscellaneous lighting and power consumers it is not possible to obtain such accurate information, owing to the more limited numbers and greater variations in consumption.

These figures are intended for use in estimating the value of new consumers and have therefore been compiled from data including only those consumers connected in recent years.

APPENDIX VI.

The load curves reproduced in the paper have been compiled from an analysis of charts obtained by means of recording ammeters placed in series with the kilowatt-hour meters on the consumers' premises. In the case of the curves relating to lighting alone the evening peak is naturally the prominent feature, but it is interesting to note that with the addition of a comparatively small amount of heating and cooking the morning load in houses exceeds that in the evening. To obtain the average weekday load is the usual object of drawing the curves, but in the case of domestic consumers week-end loads have also been investigated in order to visualize the conditions that may occur on networks supplying only these consumers. Several examples of week-end loads are given among the curves.

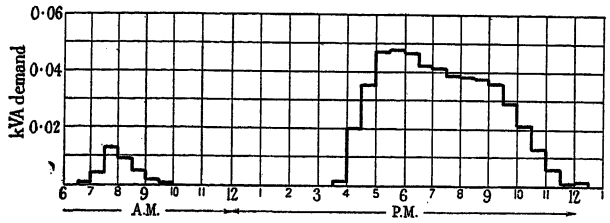


FIG. 3.—DOMESTIC SUPPLIES. Small prepayment-meter consumers. Average weekday (January) load per house. Annual consumption 84 kWh. Connections 170 watts (lighting).

The curves for domestic consumers are to some extent progressive.

Fig. 3 shows the load on a pipe-mains installation supplying lighting to typical houses in a coal-mining town.

Figs. 4, 5, and 6, show the load due to small subsidy houses with full electric equipment and one multi-purpose coal fire. The three curves here given are average weekday, Sunday, and Christmas Day, and afford an example of the influence of custom and habit on load.

Figs. 7 and 8 give the weekday and Sunday loads for typical consumers in good residential districts, who have a good standard of lighting and make use of electric labour-saving appliances, but have not yet "gone in for" heating or cooking.

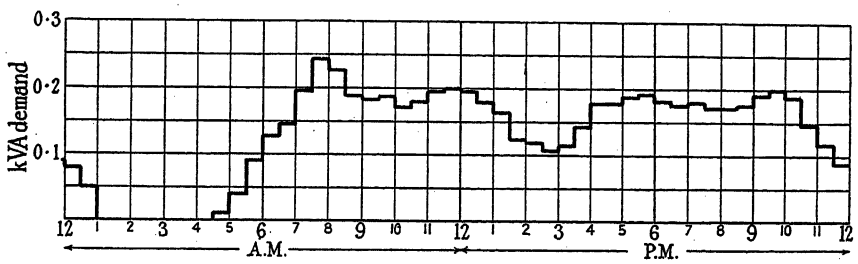


FIG. 4.—DOMESTIC SUPPLIES (lighting, heating, cooking). Council Housing Scheme, "all-electric" type with one open coal-fire incorporating water boiler and small oven. Curve represents the average weekday load per house in winter and is equivalent to 3·15 kWh. Annual consumption 900 kWh.

Connected load:—

	kW
Lighting	0·32
Cooking	5·75
Heating	2·00
Wash boiler	3·00
Kettle	1·01
Iron	0·50
Water heater	3·00
	15·58

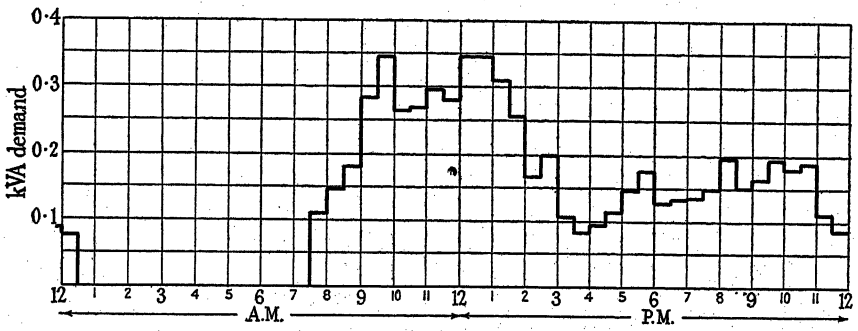


FIG. 5.—DOMESTIC SUPPLIES (lighting, heating, cooking). Council Housing Scheme, "all-electric" type. Average Sunday load per house in winter. Curve represents 3·18 kWh.

Figs. 9 and 10 show the weekday and Sunday loads obtained on a partly-developed suburban estate having no public supply other than electricity for heating and cooking.

Fig. 11 is an average weekday curve for a small house making full use of electricity.

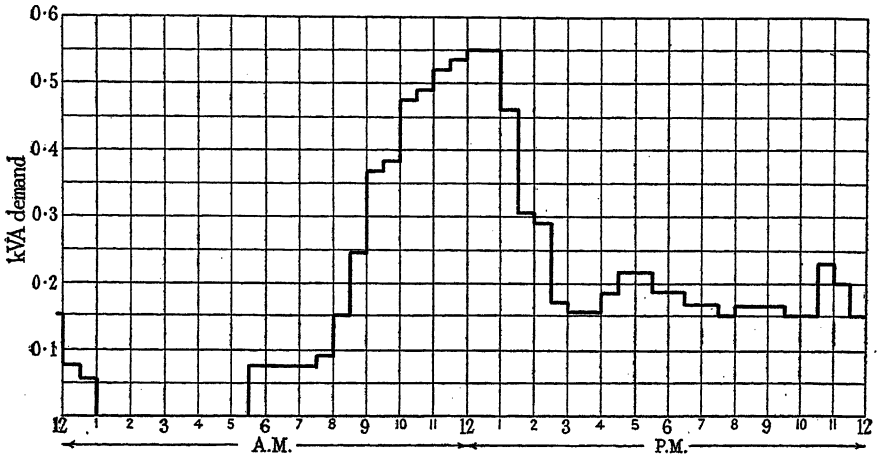


FIG. 6.—DOMESTIC SUPPLIES (lighting, heating, cooking). Council Housing Scheme, "all-electric" type. Load per house on Christmas Day. Curve represents 4·5 kWh.

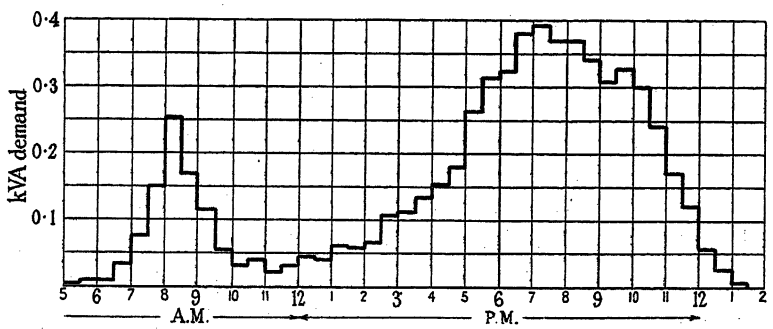


FIG. 7.—DOMESTIC SUPPLIES. Consumers on two-part tariff with lighting and small apparatus only connected. Curve shows the average weekday demand (Jan.–Feb.) for consumers having the following connections and consumption:—

Lighting	1·05 kW
Small appliances	1·0 kW (est.)
Annual consumption	750 kWh
Average no. of rooms	9·25

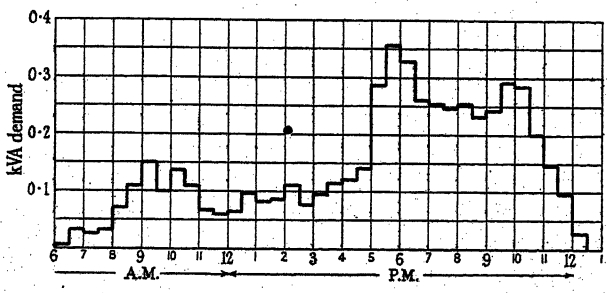


FIG. 8.—DOMESTIC SUPPLIES. Consumers on two-part tariff with lighting and small apparatus only connected. Curve shows the average Sunday demand (Jan.–Feb.) for consumers having the following connections and consumption:—

Lighting	1·05 kW
Small appliances	1·0 kW (est.)
Annual consumption	750 kWh
Average no. of rooms	9·25

Figs. 12 to 19 give lighting curves for clubs, shops, and cinematograph theatres; it is interesting to note that with each of these groups the increase in size and consumption is accompanied by a broadening-out of the load curve, indicating an improvement in load factor.

The curve for a heating installation which is reproduced in Fig. 20 is almost indistinguishable from that for a lighting load. This is due to the peculiar hours in the shape of the load curve; the following are of interest and can be seen in the curves reproduced.

Butchers:—A regular peak at 1 p.m. due to mincing the accumulation of the morning's scraps.

Boot repairers:—A decided peak in the evening when all the day's work is passed through the finishing machine.

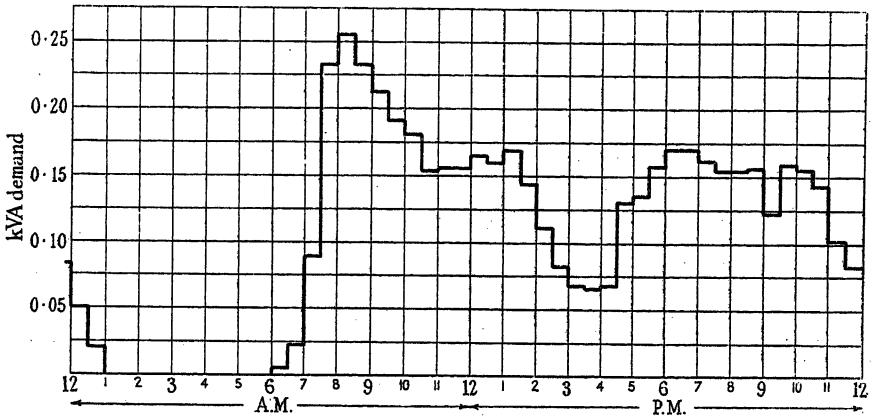


FIG. 9.—DOMESTIC SUPPLIES (lighting, heating, cooking). Average weekday load in winter per house on feeder supplying a good-class estate. Average connection per house:—

	kW
Lighting	0·625
Heating	0·875
Cooking	2·060
Appliances	0·020
	3·580

Daily curve represents 2·65 kWh.

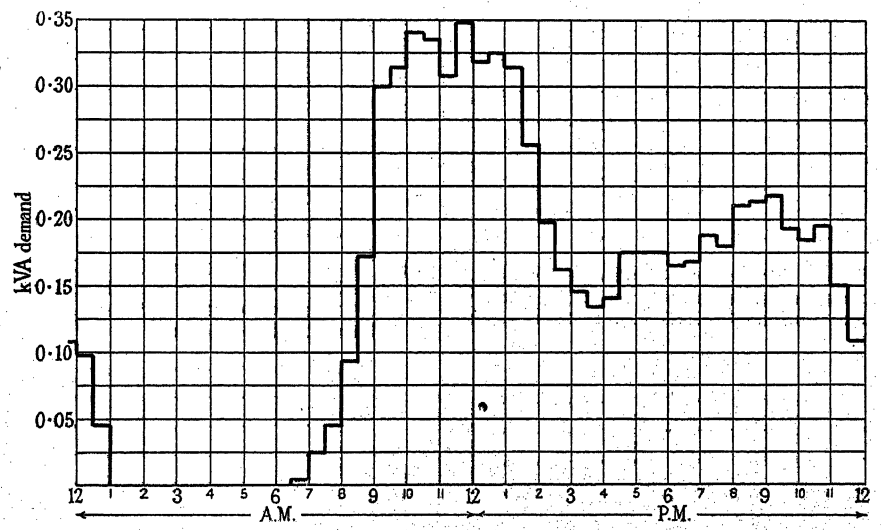


FIG. 10.—DOMESTIC SUPPLIES (lighting, heating, cooking). Average Sunday load per house on a good-class estate.

during which the building is used. Figs. 21 to 27 relate to power supplies; here the daily load curve is dependent on the hours of work and in general forms itself into two fairly solid blocks, morning and afternoon, with a slight sluggishness at the start and a falling-off towards "knocking off" time, with occasional extensions for overtime.

Certain trades provide peculiarities which are reflected

A study of load curves such as these makes it very evident how misleading load factor considered by itself may be as a criterion for judging whether a supply is of a favourable nature or not. Similar annual load factors may be obtained from very diverse daily load curves, as the annual load factor is affected by the following conditions and is usually the result of a combination of several of them.

(1) Variation in use over short periods due to peculiarities of the particular application.

(2) Variation throughout the day from midnight to midnight due to the habits or occupation of the consumer.

(3) Variation in daily use throughout the seven days of the week.

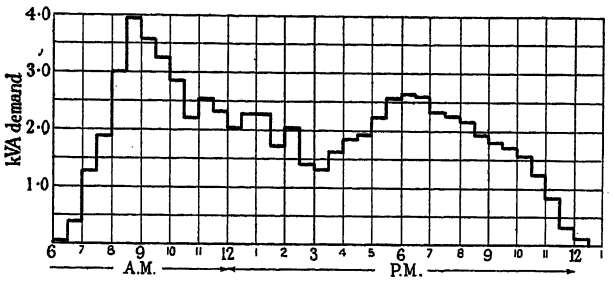


FIG. 11.—DOMESTIC SUPPLIES (lighting, heating, cooking). Average weekday load in winter for a small house where full use is made of electricity for lighting, heating, cooking, water-heating, etc. Consumption 36 kWh per day, 9 500 kWh per annum.

Connections:—	kW
Lighting	0·4
Heating	6·0
Cooking	5·8
Water heating	3·0
Wash boiler	3·0
Miscellaneous	2·5
	20·7

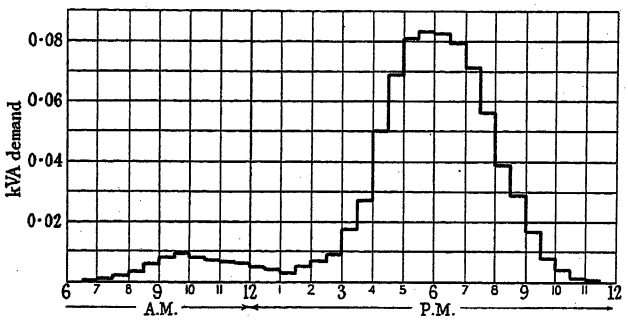


FIG. 12.—LIGHTING SHOP. Average weekday load (Dec.–Jan.) for typical suburban shops. Average connection 1·01 kW of lighting. Consumption 505 kWh per annum, based on 22 consumers.

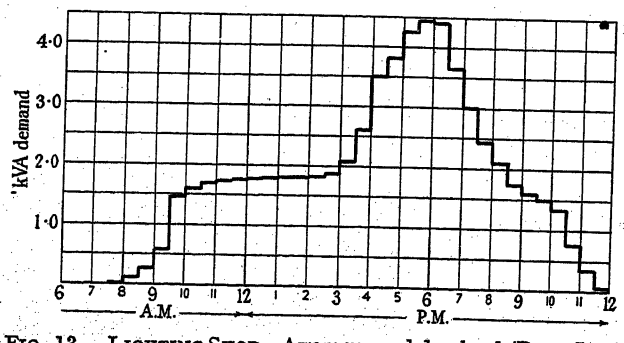


FIG. 13.—LIGHTING SHOP. Average weekday load (Dec.–Jan.) for typical shops in the main streets of a large town. Average connection 5·5 kW of lighting. Consumption 6 220 kWh per annum, based on 27 consumers.

(4) Variation throughout the year due to (*a*) variation in hours of daylight (e.g. lighting supplies), (*b*) variations in temperature (e.g. heating and refrigeration), (*c*) seasonal variations in trading conditions (e.g. fertilizer factories, road-stone quarries, etc.), (*d*) irregular variations due to such causes as industrial depression and disputes.

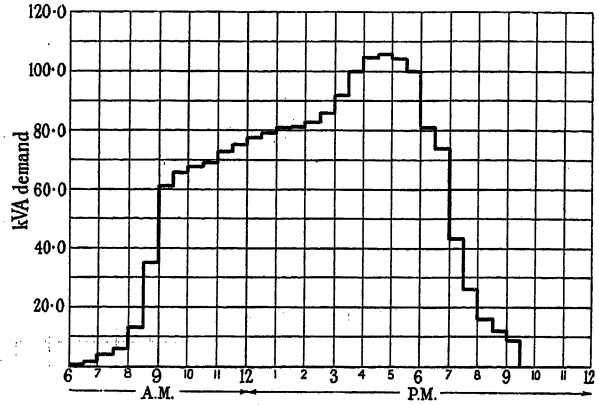


FIG. 14.—LIGHTING SHOP. Average weekday load (Dec.) for a large departmental store in a large town.

	Connections kW	Annual Consumption kWh
Lighting	128·6	155 297
Heating	12·0	12 984
Power (a.c.)	24·2	17 831
Power (d.c.)	15·0	

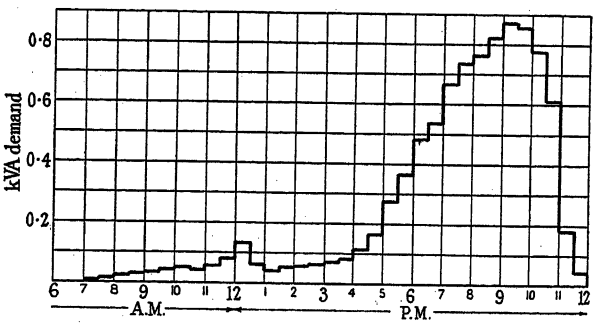


FIG. 15.—LIGHTING CLUB. Curve shows the average weekday load (Oct.–Nov.) for club buildings having 1·34 kW of lighting connected, and using 1 525 kWh per annum. Based on 4 consumers.

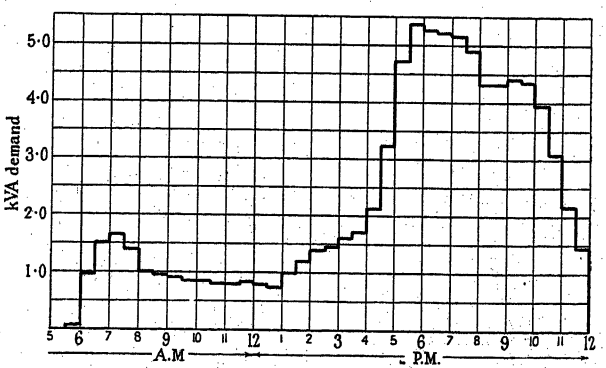


FIG. 16.—LIGHTING CLUB. Curve shows the average weekday load (Oct.–Nov.) for a club building having 11·81 kW of lighting connected and using 13 180 kWh per annum. Based on 2 consumers.

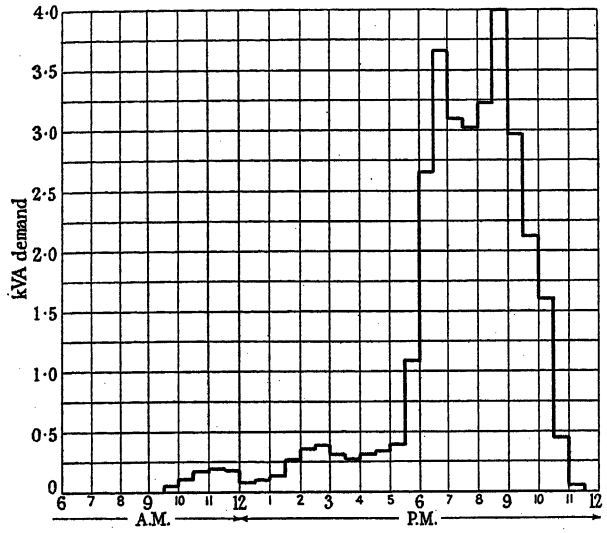


FIG. 17.—LIGHTING AND POWER. Small cinematograph theatres. Curve shows the average weekday load (Oct.) for a small picture-house having a connection of 5·43 kW (excluding spare machines), and using 6 200 kWh per annum. Based on 2 consumers.

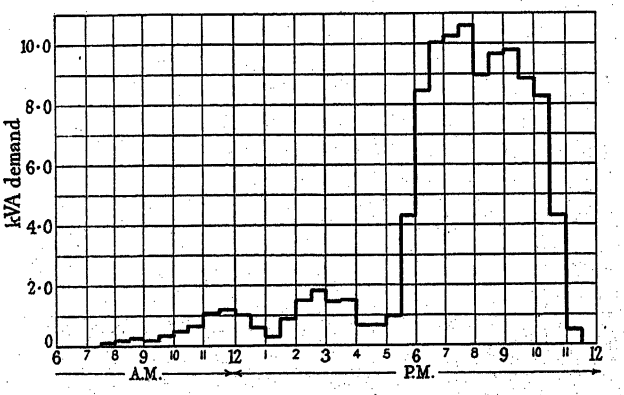


FIG. 18.—LIGHTING AND POWER. Medium-size cinematograph theatres. Curve shows the average weekday load (Oct.) for a medium-size picture-house having a connection of 27·4 kW (excluding spare machines), and using 12 850 kWh per annum. Based on 5 consumers.

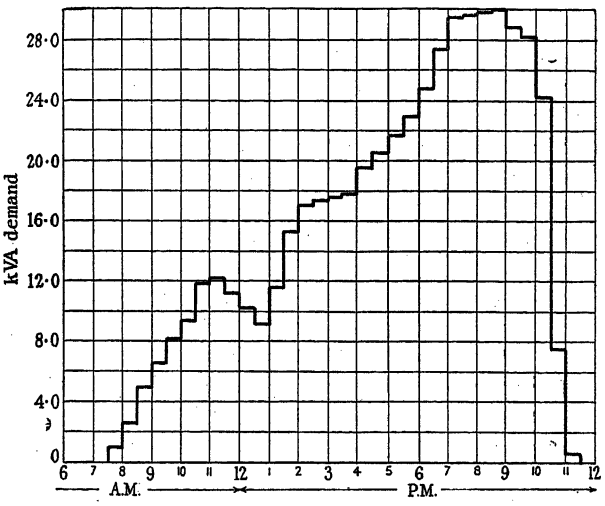


FIG. 19.—LIGHTING AND POWER. Large cinematograph theatres. Curve shows the average weekday load (Oct.) for a large picture-house having a connection of 55·7 kW (excluding spare machines), and using 80 500 kWh per annum. Based on 2 consumers.

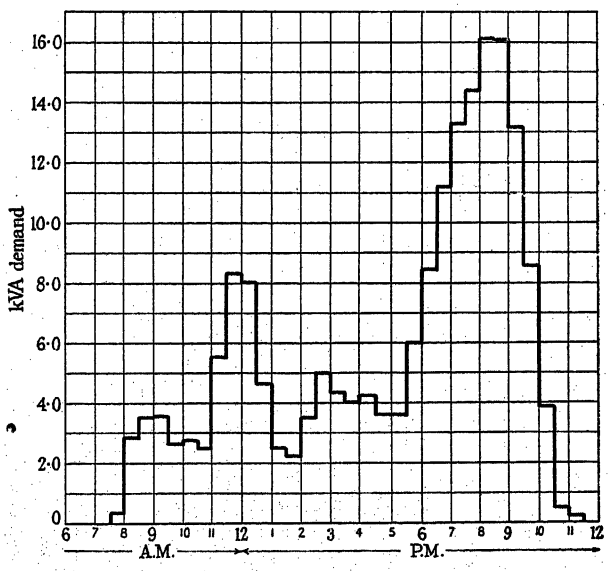


FIG. 20.—HEATING. Church-hall installation. Average weekday load. Connection 35 kW of tubular heaters. Consumption 10 180 kWh per annum. Daily curve represents 95 kWh.

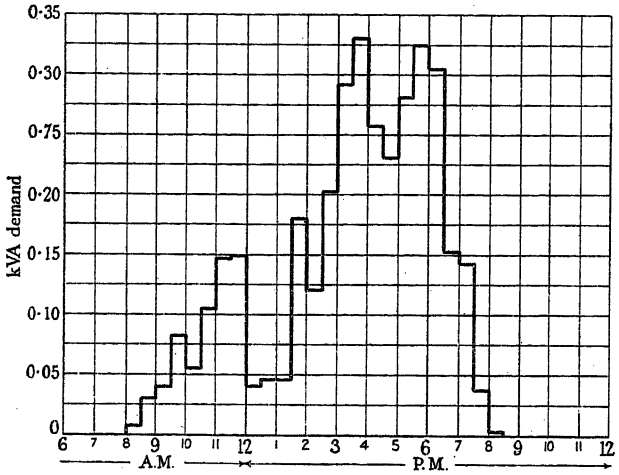


FIG. 21.—POWER. Boot repairers. Curve shows the average daily load for a consumer having 0·77 kW of power connected, and using 303 kWh per annum. Based on 8 consumers.

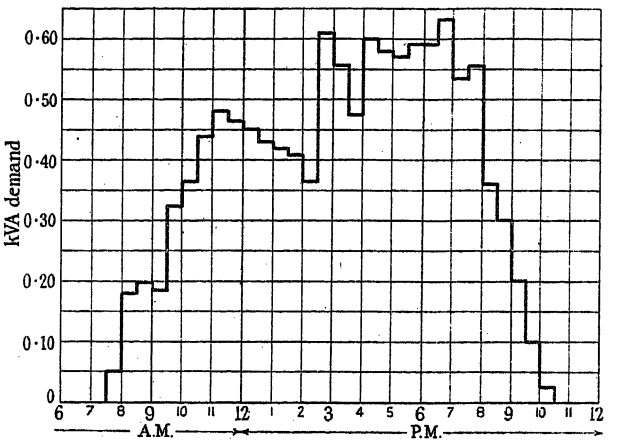


FIG. 23.—POWER. Large butchers with refrigerators. Curve shows the average weekday load for a consumer having a power connection of 3 kW, and using 1 700 kWh per annum. Based on 6 consumers.

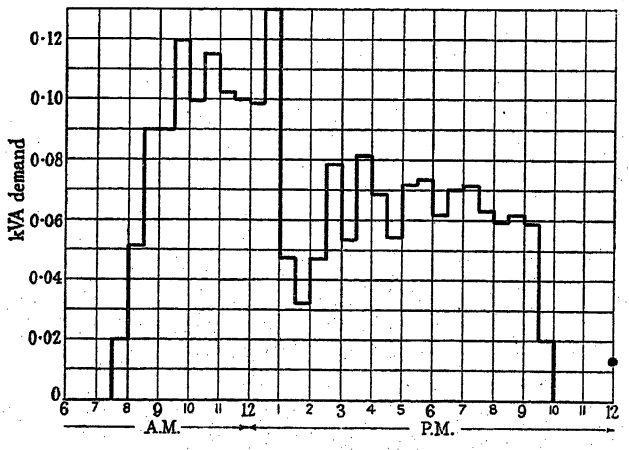


FIG. 22.—POWER. Small butchers. Curve shows the average weekday load for a consumer having a power connection of 1 kW, and using 206 kWh per annum. Based on 7 consumers.

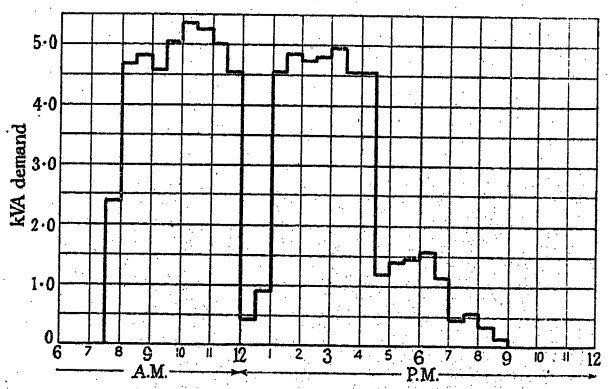


FIG. 24.—POWER. Cabinet makers. Curve shows the average weekday load for a consumer having 23 kW of power connected, and using 8 880 kWh per annum. Based on 5 consumers.

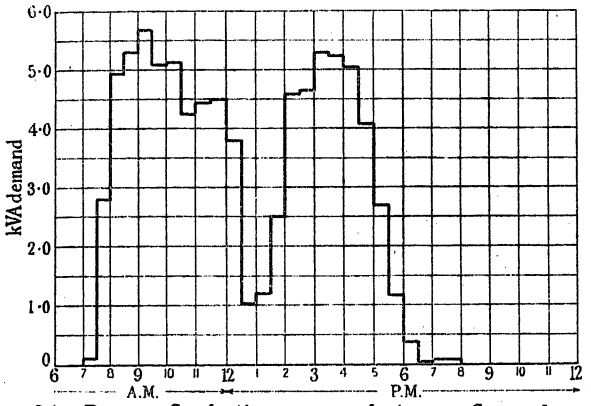


FIG. 25.—POWER. Confectionery manufacturers. Curve shows the average weekday load for a consumer having 10·64 kW of power connected, and using 8 880 kWh per annum. Based on 4 consumers.

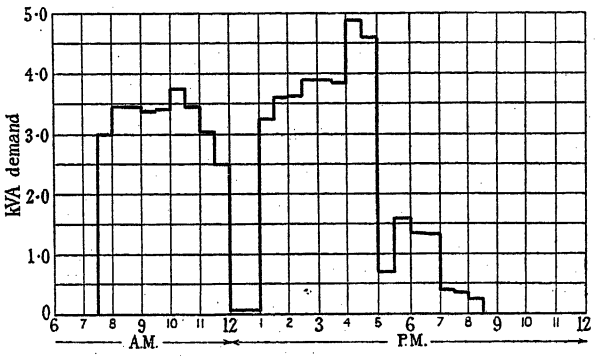


FIG. 26.—POWER. Small manufacturing engineers. Curve shows the average weekday load for a consumer having a power connection of 18·7 kW, and using 6 590 kWh per annum. Based on 6 consumers.

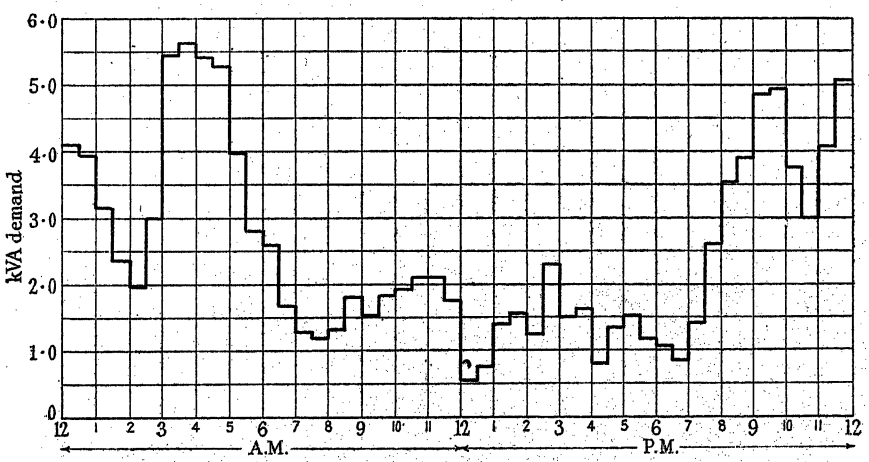


FIG. 27.—POWER. Large bakeries. Curve shows the average weekday load for a large bakery having 21·7 kW of power connected, and using 13 931 kWh per annum. Curve represents 61 kVAh.

NOTE:—The curve is for electrically-driven machinery and does not include any electric ovens. Bread is baked at night and confectionery during the day.

APPENDIX VII.

Method of Determining Average Weekday Load Curve of a Consumer from Recording-Ammeter Charts.

Premises at Heaton Road, Newcastle-upon-Tyne. Ref. No. L.B. 9.

Shop Lighting. 240 volts (d.c.). Factor = 0·1. Units for period = 46.

Date, December 1928	8.30 a.m.	9.0 a.m.	9.30 a.m.	10.0 a.m.	10.30 a.m.	11.0 a.m.	11.30 a.m.	12.0 noon	12.30 p.m.	1.0 p.m.	1.30 p.m.
Thursday, 6th	—	—	5·0	6·0	5·0	7·0	5·0	7·0	8·0	7·0	9·0
Friday, 7th	—	—	1·0	1·0	2·0	3·0	3·0	1·0	3·0	3·0	2·0
Saturday, 8th	—	—	—	2·0	10·0	8·0	5·0	6·0	1·0	5·0	9·0
Monday, 10th	—	2·0	1·0	3·0	6·0	5·0	1·0	1·0	5·0	4·0	4·0
Tuesday, 11th	—	10·0	10·0	10·0	10·0	10·0	10·0	5·0	6·0	9·0	9·0
Thursday, 13th	—	5·0	5·0	5·0	5·0	5·0	5·0	5·0	5·0	12·0	11·0
Friday, 14th	—	5·0	5·0	8·0	7·0	5·0	5·0	4·0	3·0	5·0	5·0
Saturday, 15th	2·0	1·0	2·0	5·0	5·0	5·0	5·0	5·0	7·0	9·0	8·0
Sum of divisions, 8 days	2·0	23·0	29·0	40·0	50·0	48·0	39·0	34·0	38·0	54·0	57·0
Load for average day = 4·68 kVA-hours kVA	0·006	0·069	0·087	0·120	0·150	0·144	0·117	0·102	0·114	0·162	0·171

SUMMARY OF AVERAGE WEEKDAY LOAD CURVES OF A NUMBER OF CONSUMERS USING SHOP LIGHTING.

Half-hourly Load, in kVA.

Ref. No.	No. of days	Annual consumption	Connected load	7.0 a.m.	7.30 a.m.	8.0 a.m.	8.30 a.m.	9.0 a.m	9.30 a.m.	10.0 a.m.	10.30 a.m.	11.0 a.m.	11.30 a.m.	12.0 noon	12.30 p.m.	1.0 p.m.	1.30 p.m.	2.0 p.m.
		kWh	kW															
L.B. 6	8	1 894	2·36	—	—	—	0·144	0·636	0·714	0·672	0·540	0·462	0·444	0·426	0·402	0·432	0·378	0·408
7	7	317	0·69	—	—	—	0·020	—	0·100	0·100	0·080	0·050	0·050	—	—	0·030	0·100	0·210
8	7	299	1·10	—	—	—	—	0·010	0·062	0·027	0·024	0·003	—	0·020	0·007	0·024	0·014	—
9	8	640	1·68	—	—	—	0·006	0·069	0·087	0·120	0·150	0·144	0·117	0·102	0·114	0·162	0·171	0·180
10	6	505	1·52	—	0·016	0·044	0·080	0·072	0·048	0·040	0·032	0·020	0·016	0·020	0·012	0·012	0·016	0·016
11	4	299	0·84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
12	8	246	1·00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
14	7	860	1·15	—	—	—	0·010	0·020	0·060	0·050	0·040	—	0·030	0·030	0·040	0·040	—	—
15	7	1 124	2·50	—	—	—	—	—	0·200	0·412	0·450	0·500	0·413	0·400	0·288	0·188	—	0·276
16	5	279	0·56	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
17	8	307	1·00	—	—	—	—	—	—	0·028	0·028	0·028	0·028	0·015	0·015	0·006	—	0·01
18	7	137	0·60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19	5	521	1·56	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
20	5	274	0·58	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
21	6	710	1·26	—	—	—	0·071	0·125	0·233	0·271	0·271	0·259	0·229	0·250	0·096	0·088	0·083	0·075
22	4	624	1·44	—	—	0·288	0·388	0·388	0·400	0·238	0·175	0·175	0·200	0·125	0·050	0·050	—	—
23	6	341	0·60	0·120	0·120	0·120	0·096	0·016	—	—	—	—	—	—	—	—	—	—
24	5	304	0·80	—	—	—	—	—	0·005	0·019	—	—	—	—	—	—	—	—
25	6	418	0·54	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
26	5	57	0·70	—	0·014	0·052	0·043	0·005	—	—	—	—	—	—	—	—	—	—
27	5	940	1·74	—	—	—	—	—	—	0·048	0·048	0·053	0·053	0·053	0·058	0·072	0·058	0·053
28	5	92	0·56	—	—	—	—	0·014	0·024	0·024	0·024	0·024	0·024	0·024	—	—	—	—
22 consumers	134	11 188	24·78	0·120	0·150	0·504	0·858	1·355	1·933	2·049	1·862	1·718	1·604	1·465	1·082	1·104	0·820	1·237
Average per consumer		508	1·126	0·005	0·007	0·023	0·039	0·061	0·088	0·093	0·085	0·078	0·073	0·066	0·049	0·050	0·037	0·056

APPENDIX VII.—*Continued.*

METHOD OF DETERMINING AVERAGE WEEKDAY LOAD CURVE OF A CONSUMER FROM RECORDING-AMMETER CHARTS.

Premises at Heaton Road, Newcastle-on-Tyne. Ref. No. L.B. 9.

Shop Lighting. 240 volts (d.c.). Factor = 0·1. Units for period = 46.

2.0 p.m.	2.30 p.m.	3.0 p.m.	3.30 p.m.	4.0 p.m.	4.30 p.m.	5.0 p.m.	5.30 p.m.	6.0 p.m.	6.30 p.m.	7.0 p.m.	7.30 p.m.	8.0 p.m.	8.30 p.m.	9.0 p.m.
9·0	8·0	10·0	12·0	13·0	27 0	33·0	43·0	43·0	43·0	32·0	—	—	—	—
4·0	2·0	4·0	5·0	8·0	40·0	38·0	41·0	44·0	43·0	41·0	40·0	22·0	—	—
9·0	5·0	12·0	11·0	18·0	35·0	41·0	42·0	42·0	45·0	40·0	42·0	40·0	25·0	4·0
7·0	10·0	6·0	7·0	15·0	38·0	38·0	38·0	38·0	40·0	16·0	5·0	—	—	—
9·0	8·0	8·0	30·0	38·0	38·0	38·0	43·0	42·0	40·0	24·0	—	—	—	—
7·0	8·0	10·0	25·0	35·0	40·0	42·0	45·0	43·0	40·0	20·0	8·0	—	—	—
8·0	5·0	5·0	20·0	33·0	43·0	43·0	38·0	38·0	43·0	45·0	35·0	—	—	
7·0	7·0	15·0	20·0	42·0	40·0	38·0	39·0	43·0	40·0	46·0	43·0	36·0	20·0	—
60·0	53·0	70·0	130·0	202·0	301·0	311·0	329·0	333·0	334·0	264·0	173·0	98·0	45·0	4·0
0·180	0·159	0·210	0·390	0·606	0·903	0·933	0·987	0·999	1·002	0·792	0·519	0·294	0·135	0·012

SUMMARY OF AVERAGE WEEKDAY LOAD CURVES OF A NUMBER OF CONSUMERS USING SHOP LIGHTING.—*Continued.*

HALF-HOURLY LOAD, IN KVA.

2.30 p.m.	3.0 p.m.	3.30 p.m.	4.0 p.m.	4.30 p.m.	5.0 p.m.	5.30 p.m.	6.0 p.m.	6 30 p.m.	7.0 p.m.	7.30 p.m.	8.0 p.m.	8.30 p.m.	9.0 p.m.	9.30 p.m.	10.0 p.m.	10.30 p.m.	11.0 p.m.	11.30 p.m.
0·480	0·702	0·894	1·404	1·776	1·860	1·884	1·878	1·884	1·884	1·884	1·650	0·456	0·306	0·108	0·096	0·018	—	—
0·240	0·450	0·590	0·630	0·650	0·650	0·670	0·650	0·480	0·260	0·210	0·140	0·080	—	—	—	—	—	—
0·020	0·024	0·055	0·130	0·500	0·705	0·830	0·840	0·840	0·825	0·530	0·390	0·200	0·151	0·041	0·041	—	—	—
0·159	0·210	0·390	0·606	0·903	0·933	0·987	0·999	1·002	0·792	0·519	0·294	0·135	0·012	—	—	—	—	—
0·016	0·016	0·012	0·036	0·060	0·132	0·256	0·384	0·668	0·676	0·706	0·716	0·728	0·632	0·472	0·328	0·128	0·052	—
—	—	0·038	0·170	0·544	0·712	0·744	0·705	0·764	0·770	0·756	0·775	0·582	0·506	0·344	0·011	0·005	—	—
—	—	0·040	0·190	0·540	0·610	0·680	0·730	0·750	0 830	0·770	0·770	0·770	0·770	0·720	0·390	0·180	0·090	0·090
0·010	0·060	0·180	0·390	0·850	0·950	0·870	0·900	0·910	0·820	0·810	0·810	0·830	0·780	0·650	0·415	0·250	0·220	0·160
0·475	0·512	0·588	0·825	1·860	2·320	2·360	2·340	2·330	2·290	2·230	1·580	1·212	0·662	0·313	—	—	—	—
—	—	—	—	0·060	0·180	0·370	0·400	0·460	0·460	0·460	0·460	0·430	0·270	0·020	—	—	—	—
0·006	0·019	0·028	0·035	0·256	0·490	0·835	0·835	0·835	0·835	0·775	0·463	0·269	0·091	—	—	—	—	—
—	—	0·018	0·025	0·021	0·368	0·525	0·494	0·304	0·150	0·150	0·111	0·075	0·036	—	—	—	—	—
—	—	—	0·060	0·400	0·970	1·280	1·280	1·260	1·250	1·000	0·500	0·250	0·250	0·120	—	—	—	—
—	—	—	0·070	0·180	0·380	0·490	0·520	0·520	0·500	0·280	0·220	0·110	0·110	—	—	—	—	—
0·083	0·117	0·192	0·263	0·504	0·655	0·730	0·958	0·970	0·975	0·825	0·675	0·630	0·558	0·183	—	—	—	—
—	—	0·875	0·875	0·850	1·240	1·240	1·240	1·250	1·260	0·812	0·625	0·338	—	—	—	—	—	—
—	—	—	0·024	0·132	0·256	0·272	0·300	0·300	0·300	0·300	0·300	0·288	0·136	0·052	0·024	—	—	—
—	0·014	—	0·024	0·115	0·370	0·615	0·548	0·538	0·509	0·524	0·461	0·149	0·053	—	—	—	—	—
—	—	—	—	—	0·008	0·128	0·384	0·384	0·384	0·384	0·384	0·384	0·384	0·376	0·248	0·136	0·008	—
—	—	—	0·014	0·140	0·278	0·216	0·091	—	—	—	—	—	—	—	—	—	—	—
0·034	0·024	0·043	0·144	0·595	1·140	1·440	1·440	1·440	1·440	1·440	0·780	0·380	0·300	0·024	—	—	—	—
—	—	0·010	0·019	0·043	0·158	0·456	0·480	0·442	0·436	0·408	0·370	0·370	0·370	0·370	0·370	0·312	0·024	—
1·523	2·148	3·953	5·934	10·979	15·365	17·878	18·441	18·331	17·646	15·773	12·474	8·666	6·367	3·793	1·923	1·029	0·394	0·250
0·069	0·097	0·180	0·270	0·500	0·698	0·812	0·838	0·833	0·802	0·717	0·567	0·394	0·290	0·172	0·087	0·046	0·018	0·011

APPENDIX VIII. FORM 1.

New Consumers. Date *31/12/31.*

DATA FOR PROPOSED SUPPLY AND STATEMENT OF PROFIT.

Name of Consumer *Engineering Development Co.*

Address where supply will be given *Progress Works, Wearville.*

Particulars of supply.

Supply to be given at *20 000 volts A.C. (New Substation).*

Supply to be metered at *440 volts*

Type of load		Connections, kW	Units per annum
General Engineering	*Power*	*500*	*420 000*
	Lighting	*20*	
Estimated demand			*170* kW
Estimated load factor			*28·2* per cent
Estimated power factor			*0·80*
Cost of Connection.			
(*a*) Cables			£*200*
(*b*) Substation apparatus			£*600*
(*c*) System alterations			£ *75*
Total			£*875*

Proposed Terms:—

Revenue (coal @ *12*s. per ton).

Fixed charge *£15 per month.*		£*180·0*
170 kW @ £*3·5* per kW per annum		£*595·0*
400 000 Units @ *0·35*d. per unit		£*583·4*
20 000 Units @ *0·30*d. per unit		£ *25·0*
Units @ d. per unit		£
Units @ d. per unit		£
420 000 Total units		£*1 383·4*
Discount *5* per cent on £*1 383·4*		£ *69·2*
Total net revenue		£*1 314·2*

Costs (coal @ *12*s. per ton).

141·4 kW @ £*2·203* per kW	£*311·5*
435 000 Units @ *0·1817*d. per unit	£*329·5*
1 Point of supply @ £*83·8*	£ *83·8*
Other costs, *None.*	
Total costs per annum	£*724·8*
Total profit per annum	£*589·4*

Capital and Expenditure.

141·4 kW @ £*33·14* per kW	£*4 685·9*
1 Point of supply @ £*113·3*	£ *113·3*
Special allocation (*H.V. Mains*)	£ *500·0*
New expenditure	£ *875·0*
Total capital involved	£*6 174·2*

Percentage return on total capital involved, *9·5* per cent.

NOTES.—*Half-hourly maximum demand 170 kW; efficiency factor 0·925; diversity factor 1·3; demand on power station 141·4 kW. Units per annum 420 000, efficiency factor 0·965, units delivered (high voltage) 435 000 units.*

FORM 2 (a).

Estimated by *A.B.C.* Date *31/12/31.*

Estimate for supply to *Durham Road, Wearville.*

NEW EXPENDITURE.

To afford immediate supplies.	£	s.	d.
High-voltage mains			
Substation and equipment			
Low-voltage mains	*350*	*0*	*0*
Services *less* consumers' contributions	*150*	*0*	*0*
Meters	*40*	*0*	*0*
Total	*£540*	*0s.*	*0d.*

To supply additional consumers from these mains.	£	s.	d.
Services *less* consumers' contributions	*10*	*0*	*0*
Meters	*7*	*14*	*0*
Total	*£17*	*14s.*	*0d.*

Tariff *Standard Rates for ———— Order. Primary Lighting rate 6d. per unit.*

	Consumers				Connections, kW				Estimated units per annum	Estimated net revenue
	Number	Type	Rooms	kW	Lighting	Heating	Cooking	Power		£ s. d.
Consumers requiring immediate supply	*1*	*House*	*@ 6*	*0·55*	*0·55*	*4·0*	*6·0*	—	*2 200*	*12 1 7*
	4	*Houses*	*@ 5*	*0·40*	*1·60*	—	—	—	*520*	*12 7 0*
	4	*do.*	*@ 4*	*0·25*	*1·00*	—	—	—	*400*	*9 10 0*
	14	*Slots (3 lights)*		*0·12*	*1·68*	—	—	—	*1 092*	*27 6 0*
	2	*Public houses*		*0·50*	*1·00*	—	—	—	*806*	*19 2 7*
	1	*Shop*		—	*0·10*	—	—	—	*80*	*1 18 0*
	1	*Sawmill*		—	—	—	—	*4·0*	*1 980*	*23 10 0*
	1	*Street lighting*		—	*0·60*	—	—	—	*960*	*14 0 0*
	28	—	—	—	*6·53*	*4·0*	*6·0*	*4·0*	*8 038*	*£119 15s. 2d.*
Additional consumers to be supplied from the same mains	*2*	*Houses*	*@ 5*	*0·40*	*0·80*	—	—	—	*260*	*6 3 7*
	5	*do.*	*@ 4*	*0·25*	*1·25*	—	—	—	*500*	*11 17 6*
	7	—	—	—	*2·05*	—	—	—	*760*	*£18 1s. 1d.*

Estimated present profit *£75 2s. 9d.*, giving *10·9* per cent present return on total capital involved of *£687·5.*

Estimated additional future profit *£8 15s. 0d.*, giving *11·6* per cent future return on total capital involved of *£721·2.*

FORM 2 (b).

A.C. Supply to *Durham Road, Wearville.* Date *1/1/32.*

	Present	Future
High-voltage mains	£	£
Substation and equipment	£	£
Low-voltage mains	£350·00	£
Services *less* consumers' contributions	£150·00	£10·00
Meters	£ 40·00	£ 7·70
Expenditure (including service and meters), total	£540·00	£17·70

Consumers		Connection, kW				Demand on		Units per annum	Revenue per annum
		Lighting	Heating	Cooking	Power	High-voltage system	Low-voltage system		
		kW	kW	kW	kW	kW	kW	kWh	£ s. d.
1 House @ 6 Rooms		*0·55*	*4·0*	*6·0*		*0·400*	*0·650*	*2 200*	*12 1 7*
4 Houses @ 5 Rooms		*1·60*				*0·148*	*0·296*	*520*	*12 7 0*
4 do. @ 4 Rooms		*1·00*				*0·120*	*0·240*	*400*	*9 10 0*
14 Slots (3 lights)		*1·68*				*0·322*	*0·644*	*1 092*	*27 6 0*
2 Public houses		*1·00*				*1·000*	*0·600*	*806*	*19 2 7*
1 Shop		*0·10*				*0·080*	*0·080*	*80*	*1 18 0*
1 Sawmill					*4·0*	*0·440*	*0·400*	*1 980*	*23 10 0*
1 Street lighting		*0·60*				*0·600*	*0·600*	*960*	*14 0 0*
Present total	*28*	*6·53*	*4·0*	*6·0*	*4·0*	*3·110*	*3·510*	*8 038*	*119 15s. 2d.*
2 Houses @ 5 Room		*0·80*				*0·074*	*0·148*	*260*	*£6 3 7*
5 do. @ 4 Rooms		*1·25*				*0·150*	*0·300*	*500*	*11 17 6*
Future additional	*7*	*2·05*				*0·224*	*0·448*	*760*	*£18 1s. 1d.*

PRESENT.

Costs		£
H.V. dem. *3·11* kVA @ *£1·82*		*5·66*
L.V. dem. *3·51* kVA @ *£2·314*		*8·12*
Units *8 038* p.a. @ *0·208*d.		*6·96*
Cons. (slot) *14* @ *£0·63*		*8·82*
,, (qtrly.) *houses 9* @ *£1·03*		*9·27*
,, (power) *1* @ *£1·31*		*1·31*
Other costs, *4 Consumers* @ *£1·12*		*4·48*
Total present costs		*£44·62*

Capital		£
H.V. dem. *3·11* kVA @ *£28·84*		*89·7*
L.V. dem. *3·51* kVA @ *£9·78*		*34·3*
New exp. *as above*		*540·0*
Special cap. (*Consumers*)		*23·5*
Total present capital		*£687·5*
Revenue	*£119·76*	
Costs	*£ 44·62*	
Profit	*£ 75·14*	*10·9* % retn.

FUTURE.

Additional Costs		£
H.V. dem. *0·22* kVA @ *£1·82*		*0·40*
L.V. dem. *0·45* kVA @ *£2·314*		*1·04*
Units *760* p.a. @ *0·208*d.		*0·65*
Cons. (slot) @ £		
,, (qtrly.) *houses 7* @ *£1·03*		*7·21*
,, (power) @ £		
Other costs		
Total addl. future costs		*£9·30*

Capital		£
Total present		*687·50*
H.V. dem. *0·22* kVA @ *£28·84*		*6·40*
L.V. dem. *0·45* kVA @ *£9·78*		*4·40*
Addl. new exp. *as above*		*17·70*
Special capital (*Consumers*)		*5·30*
Total future capital		*£721·30*
Addl. revenue	*£18·05*	
Addl. costs	*£ 9·30*	
Addl. profit	*£ 8·75*	
Present profit	*£75·14*	
Total future profit	*£83·89*	*11·6* % retn.

Consumer capital.

	£
23 Domestic	*17·5*
4 Miscellaneous	*4·5*
1 Power	*1·5*
	£23·5

The forms given in Appendix VIII relate to extensions involving expenditure for the purpose of connecting new consumers. Such expenditure may be on all or any of the following items: high-voltage mains, substations and substation equipment, low-voltage mains, house services, meters. The object of the forms is to set out the estimated profit and percentage return which will be obtained, not on the new expenditure only, but on the total capital involved.

Form 1 refers to Group A or Group B consumers and is completed down to and including the "Total net revenue" from information supplied by the engineer negotiating the supply, the remainder of the form being used by the statistical department for applying the cost formulæ and calculating the profit and percentage return.

Form 2 (a) is used for Group C consumers. As many hundreds of these are dealt with annually, the form is kept as simple as possible and another form, Form 2 (b), is used for the actual calculation of the costs, profit, capital involved, and percentage return.

The profit and return shown against an estimate of expenditure are taken into consideration before any such expenditure is approved; furthermore, the figures are prepared in such a form that groups of estimates can easily be summarized for the preparation of periodical statements on the anticipated results to be obtained from new business acquired during any period.

Discussion before The Institution, 14th April, 1932.

Mr. R. P. Sloan: The system described by the authors has been evolved in connection with the undertakings with which I am associated, and it forms the basis upon which we work. There are one or two general remarks which I should like to make. As the selling of electrical energy means not only the selling of "goods, wares, and merchandise" (which electricity is deemed to be in law), but also of "service," it is important to know both what the "goods" cost to produce and deliver, and also the different degrees of "service" attached to such supply. Even if the "goods" were supplied without service, it would not be so simple as it might seem to estimate the cost of production and delivery. When the national electricity scheme was being considered, the question of what was a fair costing basis to adopt as between the Central Electricity Board and the owners of selected stations (where the determination of distribution costs does not arise) was under discussion for well over a year before an agreement was reached. This instance indicates the complicated nature of the costing problems of electricity supply. To illustrate the vital importance of correct costing, one need only refer to the fact that, on the basis of the total quantity of electricity sold in this country during the year 1931, an error of 1/37th part of a penny per unit would represent the sum of £1 000 000; or, to put it another way, it would represent the equivalent of the ultimate annual amount required to meet the interest and redemption charges which the electricity supply authorities will have to provide in connection with the standardization of frequency. Supply authorities in this country are now concerned not merely with the success of their individual undertakings, but with the success of all undertakings. We have to see to it that the sales of electricity are sufficient to enable the industry to carry without injury the charges in connection with the national scheme. The necessary sales cannot be realized unless electricity is supplied not only for lighting purposes in densely populated areas, but for all domestic purposes, in both densely and thinly populated areas, and also to a much greater extent for industrial and similar purposes. This means that electricity must be sold for both "competitive" and "non-competitive" business. In dealing with supplies for non-competitive business an accurate knowledge of the cost involved by various types of supplies may not be necessary. The charges for current can be determined by the suppliers, and so long as the total income is sufficient to meet the costs, all is well. As soon, however, as competitive business begins to predominate it is essential to know with accuracy what costs are involved in supplying different kinds of loads. The charges which are possible when dealing with non-competitive business are no longer in the hands of the suppliers. There is one other matter to which I should like to refer. The authors state (page 853) that particular care is taken to avoid crediting any type of supply with advantages of a temporary nature, such as a smaller proportion than its permanent share of capital costs. In many cases sufficient attention is not paid to this point. For instance, I once heard it publicly stated by the engineer of a supply undertaking that capital charges for generating plant need not be allowed for in the cost per unit if sufficient generating plant was already in existence, and that the only charges which it was necessary to include were the cost of coal and the extra cost of generation and distribution. This engineer was quite satisfied that he need not include capital costs because he had already found the capital! Whenever capital is provided it carries capital charges, which should be shared between all those who use it.

Mr. F. W. Purse: I find myself in disagreement with the authors in regard to the general practical value of such conclusions as are arrived at in the paper. The first paragraph contains such phrases as "its value to the consumer" and "it is seldom satisfactory to sell upon a pure cost basis, as the proper price is governed by its value to the customer," and yet a little later on the authors state that "each class of supply should be debited with its true proportion of every item of cost," and also that "a standard system has the merit of facilitating equitable treatment of different consumers." These statements seem to me to be entirely contradictory. The authors have devoted much labour to a very detailed mathematical analysis of the costs of generation, but why this is necessary or of any use under existing circumstances I fail to see, as in a very short time all supply undertakings will be supplied by the Central Electricity Board on a "grid" tariff and will then not be directly concerned with the exact details of generation costs. The paper would have been more valuable if

it had dealt with the application of an assumed grid tariff. Although the authors set out elaborate tables and masses of figures to the fifth place of decimals in order to demonstrate the precise method and result of their analysis, throughout the paper we repeatedly find such statements as " These factors are necessarily of a somewhat arbitrary nature." The paper is clearly an arbitrary analysis based on average figures, and, this being so, I do not see why it is necessary to spend so much time in arriving at a result which can be of no more precise nature than figures obtained by the usual and simpler methods. On pages 857 and 858 the authors make the following statements: (*a*) " It is not correct to assume that the unit charge in a two-part tariff suitable for domestic supplies will be correct for other supplies." (*b*) A two-part tariff " can be much improved by the substitution of a sliding-scale unit rate for the single unit charge." (*c*) " A simple sliding-scale unit tariff is probably more correct from a cost point of view than any two-part tariff." I differ profoundly from the authors in these conclusions, which are justified by no proof beyond arbitrary reasoning based on average figures. With regard to all the various allocations and bases adopted by the authors, I realize that these represent their own personal opinion, but I disagree with many of them. Time will not permit of my dealing in detail with these figures, because any alteration must run through the whole of the tables and alter the final results. The figures can only apply to one particular year, as circumstances are continually altering—even from day to day. For example, the subdivision in Appendix IV between Groups A, B, and C, will vary daily and will be quite different for a succeeding year. If one does not accept the Electricity Commissioners' method of allocation of costs, which has no doubt been arrived at after much thought and investigation, is there any reason for accepting the authors' method of allocation? The paper clearly illustrates what the electricity supply industry has been suffering from almost throughout its existence, viz. " tariff disease "—a continual attempt to convert an " average " into an " exact " figure. The sooner we realize that our job is to make electricity and not tariffs, the better for all concerned.

Mr. H. Hobson: It seems to me that, despite all Mr. Purse has said, this paper is of great value to the industry, in view of the fact that it stimulates interest in a subject which has been given too little attention in the past. Although an attempt was made in America to analyse costs on a comprehensive scale, that analysis was by no means as complete or as justifiable as the one given in the present paper. In my opinion the following statement, which appears on page 852, is of more importance than the detailed analysis. " The fact that it is seldom, if ever, satisfactory or practicable to sell upon a pure cost basis, as the proper price of any commodity is governed more by its value to the customer (which must ultimately be realized to be true even under a national scheme), is no reason for neglecting a careful consideration of cost. . . ." I think this is one of the soundest remarks in the paper. However scientifically the supply industry may analyse its costs of production, it is ultimately forced to a comparison between the price charged for a particular type of service and the costs of producing that service in another way. The danger of an analysis of this kind lies in the fact that it fosters a tendency to lay down a fixed selling price for electricity. This tendency, which has hindered development in the supply industry more than any other, seems to be gaining ground just now. It seems to me that the only method of getting a general electricity supply industry in this country is to make such departures from the theoretical price based upon costing as are necessary to meet the competition of private plant, provided that the sum-total of such departures ensures for the undertaking as a whole that the total revenue raised is greater than the total cost. Almost every individual would have his own ideas of what is the proper method of allocation for a particular item of expenditure. So far as I can see, the two main difficulties are, first, the determination of the proper allowances for diversity in any particular case, and secondly, the decision as to what is the proper division between the cost at the point of supply and the cost per kW or per kVA. I should be glad if the authors would indicate in greater detail the principles which have guided them in making their decisions on these two points.

Mr. H. M. Sayers: The authors leave the capital expenditure per consumer in the form of pounds sterling per kVA, although this figure has to be expressed as an annual charge if it is to be used for price fixing. The paper allocates the cost of distribution losses to generating costs, and it undervalues them by charging them at the generating price. The cost of distribution losses is cumulative, and it culminates with the selling price for units lost through the defects of meters. If the authors were to apply to distribution plant the methods of measurement which they have applied to consumers and groups of consumers, they would obtain a good deal of useful information. The distribution losses represent nearly 22 per cent of the units sold to Group C consumers, to whom their correct costing is therefore important. With regard to rates, allocation in proportion to capital expenditure is questionable. Rates are really a form of income tax in public utility undertakings. I am particularly interested in the authors' valuable analyses of the measurement of domestic consumers' demands and consumptions. Whereas the general fashion is to adopt two-part tariffs for such consumers, they do not like the fixed charge of this type of tariff, which seems to them to amount to paying something for nothing; this is a psychological difficulty that cannot very well be overcome. The best way of avoiding the difficulty is to use classified flat rates, grouping consumers by their load characteristics, which include the diversity factor and the individual load factor. The value of service cannot be assessed in respect of small consumers of the Group C (domestic) class. The aggregate value of cleanliness, convenience, adaptability, and saving of drudgery, is not to be equated to money; therefore this value cannot be made a basis of domestic tariffs. For industrial and commercial uses the cost of competitive agencies does afford some guidance to limiting prices, though in most cases of this sort there are also accessory values not easily assessed in terms of money.

Mr. W. P. Digby: I should like to say a few words from the point of view of the Group B consumer. In cases where the load factor of this type of consumer is high, there is a discrepancy between the first paragraph on page 853 and the last paragraph in the first column of page 859. I prefer the view expressed on page 859 to that on page 853. Consumers whose load factors are better than that of the station or substation supplying them are surely worthy of special rates. Further, if consumers have been persuaded to accept the two-part tariff as reasonable—not an easy matter, as their natural bias is towards a graduated flat rate—it will be very difficult to get them to adopt the three-part tariff suggested on page 890, viz. a fixed charge of £15 per month, plus the kW charge, plus the units-consumed charge. With regard to Figs. 21 to 27, if the authors could give similar figures for consumers whose total load was of the order 150 000 to 500 000 units per annum, it would greatly add to the value of the paper.

Mr. W. J. Jones: In my opinion insufficient attention has been given in the past to distribution, which represents the major item of cost in the case of the Group C consumers. I should like further information as to the costing of sign-lighting and street-lighting loads. There is a definite endeavour on the part of supply undertakings to obtain the street-lighting load in this country at the present time. I think that it is not completely satisfactory to draw up a general system of costing without some knowledge of the trend of the particular load in question. Certain classes of load—e.g. office lighting—are known to be improving very rapidly, not only as regards consumption but also from the point of view of load factor. There is some danger in averaging the costs for a given class of consumer, because whenever new premises are equipped or a new method of lighting is introduced for such premises, there occurs a vast change in the load curve of that class of consumer.

Mr. H. C. Cooper: "Cost accounting" should be clearly distinguished from "chartered accounting." The work of the chartered accountant consists principally in making accounts balance to the last penny, while the cost accountant endeavours to analyse the figures in order to find out where economies can be made and to forecast future results. The cost accountant's figures are necessarily based to some extent on estimates and assumptions, and their preparation involves more knowledge of engineering than of accountancy. I disagree with the authors' method of estimating the cost of new supplies without taking into account the capital charges. The examples which they give show that the difference between the anticipated revenue and the cost of supply would be equivalent to between 9·5 and 11·6 per cent of the capital involved, from which it appears that the supplies in question could be given at a profit. If, however, the return had come to, say, 7 or 8 per cent, it would have been impossible to decide whether this would cover interest on capital and also depreciation of plant. In my opinion it is better always to take into account such charges at the outset. Both items are difficult to assess, but it is surely better to have an approximate figure, which can be adjusted if necessary, than none at all. In order that the supply in question may take its share in profit earning, the interest rate should be not less than that for the whole undertaking. This figure cannot be ascertained until the year's results are known, but an average for two or three previous years is close enough. The payments for writing-off plant present a more complicated problem. In practice the amount allocated for this purpose in any year will depend upon whether funds are available, and on other factors. It is usually preferable to ignore the figures in the accounts and to calculate the amounts which should be paid. The calculation is based on the requirement that at the end of the life of the plant in question funds shall be available to replace it with identical plant, and it is assumed that a special fund exists into which the payments are made and from which replacement plant is purchased. This fund will, of course, earn interest. Two factors must here be considered; first that market prices may have changed by

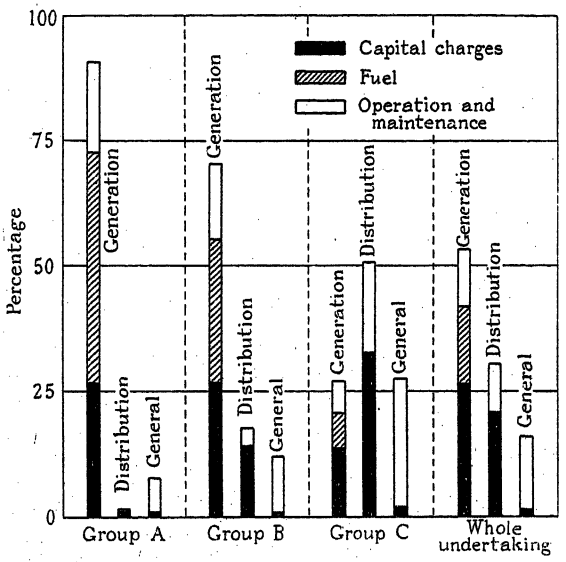


FIG. A.—Cost of electricity supply to various classes of consumers.

the time that the plant is due for replacement, and second, that it may be replaced by plant of a new and more costly design in order to obtain increased efficiency. Neither factor, however, presents any real difficulty. Fluctuations in market prices are a matter for the general reserves of the company and are no more important than other unforeseen contingencies; while if expensive plant is used for replacement purposes the company's assets will be increased in value, which is a matter for additional capital. The first step is to estimate for each class of plant the life to be expected before it must be replaced, due to its being either worn-out or obsolete. Low-efficiency plant is likely to be replaced after a comparatively short life owing to replacements of higher efficiency becoming available, while high-efficiency plant will be retained in use for a much longer period. The scrap value must also be estimated. It is then a simple matter to find from interest tables what annual payment is required. For example, with a 20-year life and 10 per cent scrap value, the annual payments would be 2·7 per cent of the first cost, assum-

ing interest at 5 per cent to be earned by the fund. The rate of interest taken in this calculation should be the average earned by the undertaking, less any necessary allowance for income tax. In order to illustrate the importance of these capital charges I have prepared a set of graphs (Fig. A) for each group of consumers and for the undertaking as a whole. These graphs are based on the authors' figures, except that I have adjusted them to allow for the generation of the whole of the current and so made them more generally applicable. Interest on capital has been taken at 6 per cent, and depreciation-fund payments at 2·7 per cent on the power station and 1·5 per cent on the distribution system. These figures are only approximate, but they are sufficiently close to illustrate the point. After allocating the costs to the three groups of consumers, the authors split these costs into fixed and unit charges. Apart from generating costs, the only unit charge is that for the Electricity Commissioners. In my opinion, some part of the cost of substations and mains should be variable, even if it is a small one. Interest on coal stocks is referred to as a unit charge, but I have not been able to find it among the figures given in the paper. A point which seems to require further explanation is that the cost of current purchased works out at 0·5d. per unit, while the generation cost (including capital charges) is only about 0·34d. per unit.

Mr. D. J. Bolton: There are considerable objections to the authors' method of taking capital charges into consideration. They treat each consumer as though he were a commercial enterprise earning a certain rate of interest. As Mr. Cooper has pointed out, this system makes it difficult to compare one undertaking with another, or one operation with another. An operation which was justified, say, in 1910, might not be justified in 1920 owing to higher rates of interest, and might become feasible again in 1930 because the rates of interest were less. The cost analysis should surely show this. The authors' system also makes it impossible to allow for variations in the lives of the different items of plant. In comparing two different undertakings it is obvious that if one undertaking can borrow capital at 5 per cent, and another has to pay 7 per cent, the difference is just as important and relevant to the cost analysis as if one undertaking can buy cheap coal and the other cannot. Further, as the authors do not divide the capital expenditure on the generating stations among the various parts, it is difficult to see how they can distinguish between the expenditure proportional to kW and the expenditure proportional to kVA. It is essential to be able to do this if ultimately a power-factor tariff is to be employed. Since the authors divide up many of the items of expenditure minutely, it is curious to find a major item such as this left undissected. In the paper all the costs, except the generating working costs, are regarded as fixed charges, although the transmission and distribution working expenses must vary slightly with the number of units supplied. It seems to me better to allow the same allocation of distribution working expenses between fixed and running charges as that employed for generation (excluding fuel). The authors point out on page 857 that a purely "costs" tariff will often give too high a fixed charge and too low a running charge. A high fixed charge frightens the small consumers and is inequitable because the low-load-factor consumer pays more heavily than he should, owing to his potentially better diversity factor. Thus if there are two consumers taking the same number of units, one having a load factor of 5 per cent and the other a load factor of 50 per cent, the one pays 10 times as much fixed charge as the other, although he (with others of his kind) does not monopolize 10 times as much plant. In my opinion the only way of making up the balance to a low-load-factor consumer is to increase the running cost and decrease the fixed cost. The change should be based on the assumption that the individual diversity factor is equal to the reciprocal of the load factor raised to some power less than unity.

Mr. J. W. Rissik: The paper may be compared to an algebraic formula made up of several independent variables. We all know how difficult it is to state facts in the shape of a formula: the labour involved is always great, but when the formula has been found the labour has been expended once for all. We cannot, however, apply the formula until we have determined the numerical values of the several factors of which it is made up. This is the second difficulty to be overcome. If the numerical values of all the factors have been determined, but one is incorrectly assessed, the final result obtained by the formula is wrong, and all the labour expended in estimating the other factors has been in vain. Whilst the authors show how to assess most of the factors, the paper has a serious defect in that it contains very little information as to how to determine the diversity factor. I should be glad if the authors would explain in detail (*a*) how the demands in the second column of page 869 (Appendix IV) were determined. Presumably these are the effective demands, and not the algebraic sum of the individual demands of the consumers in groups A, B, and C. If so, how was the diversity factor obtained? (*b*) To arrive at the consumers' effective demand on the power station the authors apply an efficiency factor and a variable diversity factor (1 to 1·5). These depend, apparently, on the load factor and other conditions. It would be interesting to know exactly how they depend on these variables, and how the authors would define the efficiency factor. (*c*) I should be glad if the authors would explain further the meaning of "half diversity" factor (page 861). (*d*) In Table 8 the effective demand on the low-tension network is in some cases shown as greater than on the high-tension system. How is this possible?

Mr. J. N. R. Perks: The basis of the authors' costing system seems to be the relationship between the maximum demand on the power station and the capital and annual costs of the supply. Previous speakers have pointed out that that relationship varies from year to year, and I think that in devising tariffs—particularly for power consumers with contracts of 5 years or more—regard must be had to what that relationship will be in future years. I therefore suggest that it would have been better if the authors had given a little more attention to estimates of future loads and a little less to minute subdivisions of certain items of present cost. As regards Appendix III, it is difficult to agree that because the demand of a power consumer increases,

say, from 200 to 400 kW, the amount of the secretary's time debited to that consumer should be doubled. I have tried for some time past to discover whether overhead costs follow any law, and in preparing estimates for the distribution companies with which I am associated one of my colleagues discovered that the overhead costs of these companies (see Fig. B) can be expressed by the equation

$$y = a + b \log_{10} x$$

where a and b are constants, y is the overhead cost, and x is the number of consumers. The points, which represent the actual overhead costs of four different distribution

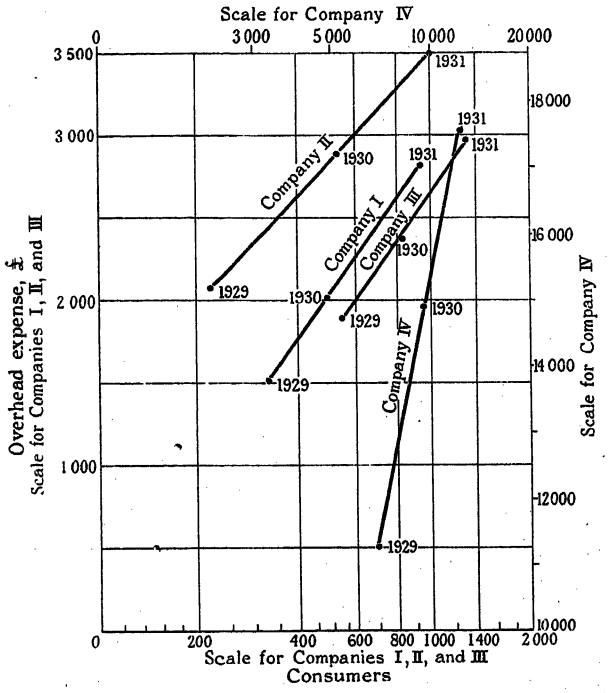


FIG. B.—Relation between overhead expenses and number of consumers. (Overhead expenses include management, directors' fees, accounts department, Electricity Commissioners' and Central Electricity Board's expenses, rents, rates, and transport.)

companies for the last 3 years, are plotted on a logarithmic scale and will be seen to lie on a straight line for each company. The authors state that they make no allowance for the distance from the source of supply. As a general rule, the costs of transmission vary as the square of the distance and inversely as the square of the voltage; disregard of distance may result in a consumer being taken on at considerable loss. The paper will perhaps restrain engineers from the somewhat prevalent habit of selling electricity at any price, irrespective of costs.

Mr. J. I. Bernard: Electricity-supply costs can be analysed fairly exactly and—as far as I am able to judge—correctly by the authors' methods, but the task of dividing the cost between the various types of consumers in any group is not so easy, chiefly because of the varying conditions of use. Turning to page 857, I think that further analysis of the costs that should be ascribed to the most numerous (and lately the most remunerative) class of consumer, i.e. the domestic consumer, would be of great value to those supply engineers who are not so much concerned about the division of expense as about the method of allocating fixed and running costs to the various classes of consumers. It would seem, therefore, that further and more rigorous analyses of the type given in Tables 4 to 9 are necessary in order to make the calculations cover most practical cases. Tables 4 to 6 emphasize the value of the domestic consumer. They show, for example, that the load factor of the ordinary house increases steadily from 20 per cent (on effective low-voltage demand) for lighting only, to 29 per cent for a Council house with fairly full electrical equipment, to 38 per cent for a medium-size house using heating and cooking, and up to 44 per cent for a fully-electrified house. Table 6 barely covers all the probable conditions of use: the authors state that time of incidence and duration of maximum demand have been taken into consideration in assessing the effective demand, but as the figures for the majority of partly-electrified homes fall between those given in the last two lines of the table, it would be very useful if intermediate cases could be quoted. On page 857 the authors attack established ideas on tariffs; I suggest that it would have been better if they had either omitted these remarks or else gone a stage further and proved them to be true. As regards their view that it is not right to make the same unit charge for a shop as for a house, the point that strikes me most in the general analysis is that all low-voltage-consumer costs are reduced to fixed charges, with the sole exception of the unit charge of 0·208d. (the working cost at the power station), and the unit consumptions of all the consumers in the road taken in the second example (page 891) of Appendix VIII are lumped together and charged at 0·208d. Turning to the figures of cost given in Appendix IV, I suggest that insufficient amounts are allowed for the selling organization, on which the success of the undertaking will largely depend. It would be more appropriate, too, if the figures for the cost of the sales and publicity departments were shown under a separate heading. The relatively small amount quoted for advertising should not be sandwiched between the charges for stamps and for gratuities. Similarly, when £3 800 is allowed for a statistical department, an expenditure of £1 280 on showrooms is inadequate. Greater amounts are allowed for "consumers' departments," but without an exact knowledge of what is included it is difficult to appreciate the position.

Mr. J. R. Blaikie (*communicated*): It would be instructive if the authors would explain in detail how the total demand is subdivided, in practice, for allocation to the three groups. On page 862 the fixed proportion of the fuel cost is stated to vary directly as the demand. A Parsons line does not confirm this, and some observations which I have made recently, on a daily basis, suggest the equation

$$A + (B \times \text{kW}) + (C \times \text{kWh}) = \text{Total cost of fuel}$$

where A, B, and C, are constants. (B is of the order of £5.) At about 50 per cent load factor it appears that approximately 40 per cent of the fixed proportion

of the fuel cost is a constant. Some engineers who have abandoned load-factor tariffs have boldly disregarded the fixed proportion of the fuel cost and have considered instead the total average fuel cost. This seems to be rather a crude method, however, having regard to the Parsons line. It has occurred to me that the fixed proportion of the fuel cost may be related to the cost of the fixed losses in the mains, transformers, and meters. This might be reckoned on a mileage basis, and indirectly become a consumers' charge. The authors' opinion on the correct division of the fixed and running proportions of repairs and maintenance costs would be valued. As regards the fallacy of allocating the whole of the mains capital charges to the kW demand, surely a substantial portion of this cost should be allocated per consumer; it is far more important to sell the maximum number of units per mile of main, at any load factor, than to aim at increasing much art and skill is necessary in selling electricity as in disposing of any other product. The framing of sound alternative tariffs necessitates knowledge acquired in the first place by a careful analysis of actual costs, and fortified later by experience. Rapid as has been the recent growth in the total output of electricity, it is not yet fast enough to ensure that the object of the national scheme will be achieved as soon as was at first anticipated. In order to stimulate consumption we must be ready to offer the consumer the system of charging which most appeals to him, always provided that the tariff covers the cost and allows for a reasonable return on capital. The statement that the price of any commodity is governed more by its value to the customer than by its cost, is open to qualification. One school of thought maintains that current should be sold at the highest price obtainable, and another considers that it should be retailed at the lowest price that will cover

TABLE A.

Consumers	Estimated revenue	Costs	Profit	Capital	
	£ s. d.	£ s. d.	£ s. d.	£	Per cent
1 house at 6 rooms	12 1 7	5 2 9	6 18 10	92·3	7·5
4 houses at 5 rooms	12 7 0	5 9 6	6 17 6	64·34	11·4
4 houses at 4 rooms	9 10 0	5 4 10	4 5 2	58·06	7·3
14 slots (3 lights)	27 6 0	11 16 2	15 9 10	191·35	8·1
2 public houses	19 2 7	6 9 8	12 12 11	118·05	11·2
1 shop	1 18 0	1 7 8	10 4	17·85	2·9
1 sawmill	23 10 0	4 13 9	18 16 3	63·25	29·5
1 street lighting	14 0 0	4 8 0	9 12 0	82·2	11·6
	£119 15 2	£44 12 4	£75 2 10	£687·50	10·9

the load factor. Such items as the Electricity Commissioners' charges should be divided by the total number of units; if this were done there would be much less difference between the overall costs at 20 per cent and at 30 per cent load factor. I suggest that the majority of the tariff troubles of the past have been due to an exaggerated idea of load-factor costs. The authors multiply the three components of the cost, viz. the consumers' charge, the kW charge, and the unit charge, by a common factor in order to obtain the necessary gross profit for meeting the capital charges. Although the purist might object to this method on the ground that the greater part of the capital charges are per kW, I think it is a move in the right direction. I should, however, prefer to see the kW charge relieved of every allocation that is not positively justified, in the original analysis. The step rate in the unit charge, inside a load-factor tariff, seems to call for some explanation.

Sir Arnold Gridley (*communicated*): In some areas the policy is pursued of rigidly adhering to a limited number of tariffs. Is there not a strong case, however, for entrusting the engineers whose duty it is to get business, with a fair number of alternative tariffs? A consumer may be secured by one tariff definitely refuse another. At least as all charges. Which of these two policies is likely to cause the more rapid increase in the consumption of electricity? If, as is claimed by those engaged in the industry, electricity supply has become as essential a public service as water, gas, and rapid transport, does it not follow that current must be sold at the lowest price which will enable a reasonable dividend (comparable with that paid on gas stocks) to be earned? If so, there is room for a revision of tariffs in many areas where current is being sold inequitably as between one class of user and another. In some districts the lighting and domestic rates are too low, and power tariffs far too high. In other areas the reverse is the case. Is not this position in some degree due to the lack of knowledge of the true costs of delivering current to the various classes of users?

Mr. C. H. Hird (*communicated*): The authors' classification of consumers into three groups will no doubt enable most supply undertakings to apportion with accuracy the costs of the greater part of their output. The large consumers of Groups A and B can be readily placed in their proper categories, and each of these groups has its definite characteristics. Group C, in which the remaining consumers are placed, contains such a variety of types that for many purposes further subdivisions would seem desirable. With regard to

the mains extension considered on page 891, in Appendix III the authors point out that it must be incorrect to allocate costs to the consumers on the basis of their demands. Unless allocation is made, however, much of the value of the analysis is lost, and it will be of little assistance in such questions as the fixing of tariffs for the various types of consumers in Group C. Table A represents an attempt at this allocation, bearing in mind that the expenditure on low-tension mains is only a little more than one-half the total capital involved. In actual practice, allowances could be made in abnormal cases, which would remove the most serious sources of error. As the authors point out, the proper price of a commodity is governed by its value to the customer, and there is no reason to suppose that the sawmill referred to in Table A is being overcharged for the services rendered by the undertaking. Nevertheless, if this consumer had not been included the profits from the extension would have been lower by nearly 2 per cent. The supply to the 14 consumers with 3 lights each is of particular interest, as many undertakings are seeking domestic loads to maintain their output at a time when the demands of industry are stagnant. Only a small proportion of houses having 5 rooms or less are wired for electric light. Table B* gives some idea of the potential load awaiting development amongst very small lighting consumers.

TABLE B.

	Percentage of total number of houses where the number of rooms per house is—			
	1 to 3	4 to 5	6 to 8	9 or more
	per cent	per cent	per cent	per cent
London	18	27·1	42·4	12·5
Manchester	11·8	65·8	20	2·4
West Riding of Yorkshire	33·8	48·3	15·5	2·4

The figures given on page 892 show the slot-meter consumer's cost as £0·63 and that for the quarterly-meter consumer as £1·03; it would be interesting to know the reasons for this difference, as an additional charge for slot-meter maintenance might have been expected. The value (at 0·208d. per unit) of the units passed through each slot meter is less than 1s. 4½d. per annum, and it seems paradoxical to install apparatus at a cost of £2 or more to measure such a small quantity. It is practicable to supply consumers of this type at a fixed charge and allow unlimited use, as has long been the practice of water companies. In certain districts in and near London this method has been adopted, the consumers being connected in groups of about 8 to each service. Statistics of such supplies are as follows:—

Consumers	20 500
Lamps	58 500
Lamps per consumer	2·85
kW connected	2 470
Units per annum	7 200 000

From the above it appears that a small consumer supplied with unmetered electricity will increase his consumption to about 4 times the number of units he would use if connected through a slot meter. The additional cost of these units at the above rate does not amount to more than is usually charged as meter rental. The very small domestic consumer calls for special methods of supply, and there is a danger that when grouped with consumers of other types he may be an unsuspected source of loss to an undertaking.

Mr. C. E. Sayer (*communicated*): The example of the analysis of electric supply costs presented in this paper is, in my opinion, very valuable, and I am interested to see that it follows closely the lines of a hypothetical analysis which I myself worked out some years ago as an example of tariff building. Whether or not the results obtained are strictly followed in the actual tariffs quoted, it is, I think, of the greatest importance, as some previous speakers have pointed out, to know what is the real cost for any particular class of consumer. There are, of course, wide limits in respect of the elaboration with which such an analysis can be conducted, and it may perhaps with some justification be thought that the degree to which this has been carried by the authors goes beyond what is necessary for ordinary purposes. I should like to suggest an addition to the interesting results given in Figs. 3 to 11. This is the average floor area of the respective premises. I believe it is generally conceded that the floor-area basis for domestic premises forms, on the whole, undoubtedly the best for quarterly fixed-charge computation for two-part tariffs, and this information would provide a valuable link between floor area and demand. These charts, with the data accompanying them, do give information as to average load factor and apparently take account of the class diversity-factor. That is to say, if the demand read off the diagram for any hour of the day be multiplied by the number of consumers, the result gives the actual load to be expected from that number of consumers of the class in question. The diagrams do not, however, indicate what the diversity factor for each class actually is, so that the addition of some information on this point would be of value.

[The authors' reply to this discussion will be found on page 905.]

* See W. B. WOODHOUSE: *Journal I.E.E.*, 1925, vol. 63, p. 3.

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 4TH APRIL, 1932.

Mr. O. W. Minshull: I should like to know whether the authors have come to any definite conclusion as to which method of inducing the bulk consumers to take their supply at a reasonably high power factor is the most satisfactory from the supply authority's point of view. Presumably the authors agree that some form of penalty for a low power factor, or rebate for a high one, is necessary, since they allow for an adjustment where the power factor differs appreciably from the average for the group. A low power factor being of no benefit

either to the supply authority or to the consumer causing it, the analysis of costs should show that the cost to the supply authority of the inducement to improve power factor would be recovered by the saving in capital expenditure alone, more especially in the case of Group B consumers. The natural corollary is that Group A consumers be offered practically no inducement to improve their power factor.

Mr. R. H. Rawll: Although it would appear that the supply undertaking with which the authors are associated utilizes the very detailed analysis outlined in the paper as a practical basis on which to fix the tariff for a particular class of load, the smaller undertakings in this country could not hope to maintain a statistical organization for a similar purpose; it does not necessarily follow, however, that the information put forward by the authors is of little value to such undertakings. On the contrary, much of the matter contained in the paper is of great value to undertakings of all sizes. For example, a comparison between Figs. 9 and 11 gives a good idea of the amount of potential load available in the domestic sphere. It shows that the average consumption per house is approximately 7½ per cent of that of the individual house where full use is made of electricity, and, incidentally, it also shows that the peak load on the feeder would be increased 16 times if all houses were fully electrified. Again, it is apparent from these two curves that the morning peak is about 50 per cent higher than that of the evening. Fig. 10 shows that the maximum load is obtained on a Sunday morning and that it is about 40 per cent higher than the weekday-morning peak. The Sunday-morning peak is also more prolonged, in that the load does not fall off until after midday, whereas on weekdays the load rapidly declines after about 9 a.m. A study of the various curves in the paper gives food for thought with regard to the supply meters of abnormally large current-carrying capacity which are often installed to-day by many supply authorities in order that they may be on the safe side in relation to the connected load. It would be interesting to know what type of domestic water-heater is installed in the house whose load curve is shown in Fig. 11, since there appears to be no load at all during the night. Supply authorities are giving special rates for night loads, and water-heaters with thermostatic control fulfil this condition; but they do not appear to be utilized in this particular instance.

[The authors' reply to this discussion will be found on page 905.]

North-Eastern Centre, at Newcastle, 11th April, 1932.

Mr. C. Turnbull: From the mathematical point of view the problem of charges to bring in enough money is similar to that of solving an indeterminate equation with a large number of variables. An infinite number of solutions is possible, but by making use of the principles set out in the paper one can considerably reduce the number and discover those that are correct. In practice it is impossible to be entirely scientific, as ultimately one has to be guided to a large extent by what can be charged commercially. From a theoretical point of view every consumer should be charged a yearly sum to cover the cost of his service, whether he uses current or not. This brings one face to face with the difficulty that the cost of supplying a small house with a long garden may be greater than that of supplying a large house close to the mains. Although the Garden City movement is excellent from one point of view, it greatly increases the cost of the electricity, gas, and water supplies, and it would be advantageous to everyone if all these mains could be laid close to the houses instead of in the roads and separated from the houses by long gardens. While one cannot get those concerned to see that the cost of supplying houses is a matter which affects consumers, the fact remains that in the end the consumers have to pay for excessively expensive mains. There is an opportunity here for useful co-operation of supply engineers with architects and town planners. The paper makes it clear that one must be cautious in dealing with special tariffs for heating, etc. Where bulk supplies are taken, a large heating load may place an undertaking in a difficult position. A cold snap in December may increase the maximum demand by hundreds of kilowatts and raise the kilowatt charge by £1000 or more, without producing any appreciable revenue. In January an equal increase in the demand may be much less serious, seeing that it will probably be compensated for by the normal increase of load before the end of the year (the kilowatt charge is usually based on the highest demand in the calendar year). No amount of calculation will enable one to predict such items as these, and they must be allowed for under "contingencies." A further item in the problem of costs is the effect which tariffs have on load curves. Where current is cheap the load factor will tend to be high, and when it is dear the load factor will tend to be poor. The authors' method of calculation will help supply authorities to estimate the rates which may be offered to consumers in order to induce them to improve their load factors. In the end, the problem resolves itself into a balancing of mathematical costs against the psychology of consumers. Mathematically, the fixed charge should be high and the running charge low; but in actual practice it may be found that consumers are afraid of high fixed charges, and they may prefer to have a lower fixed charge and a higher running charge. The principles of costing discussed by the authors apply to manufactures generally. The time and material necessary for the manufacture of almost all kinds of articles only represent a fraction of the total cost, and manufacturers are discovering that once they have obtained their establishment charges they can make a profit by selling the balance of their products at a low price. There is a precise analogy between this and the system of selling electricity for heating at a lower price than for lighting.

Mr. C. W. Salt: The authors examine the question of cost analysis from the point of view of an undertaking owned by a company. No reference is made to interest and sinking-fund charges, and if the figures under the heading of taxes include income tax the amount charged is small as compared with other items such as rates.

Presumably these items are treated as an appropriation of profit, and not as a charge. The percentage returns referred to on page 892 will indicate whether these charges are covered. With a municipally-owned undertaking, where such return is insufficient to cover the charges a net loss is the result. There is no reason why provision could not be made for this in ordinary circumstances. A complication occurs where capital expenditure of a considerable amount entails a corresponding increase in the interest and loan-repayment charges. The amount of spare plant is increased and the required percentage return on allocated capital is more. This means that for a given extension for the year before the new charges are met, the percentage return would be considered adequate, whereas for the following year it would not. Further, the relation of the cost of one type of asset to that of another is constantly changing, and the depreciation charges due to the differing periods of life are thus fluctuating proportions. I have in mind that the period of life assigned to various assets in municipal undertakings may vary from 7 to 40 years. Here also the system of amortization can be the means of increasing capital charges by steep steps. The authors appear to allocate capital expenditure to groups irrespective of the differing lives of the assets. Should these not be weighted? Moreover, in view of the fact that the "grid" price will allow for generation capital charges only, would it not be an advantage, particularly where a grid supply is taken, to separate generation from distribution capital expenditure and have separate components for each? In view of the fact that a great deal depends upon the accurate apportionment of kW and kVA between groups of consumers, I cannot see that the majority of undertakings are in a position accurately to determine such components in their application to groups. As a universal costing system, therefore, the value of the authors' scheme would be lessened. Without an accurate analysis of costs it is impossible to construct a tariff which will give equality of treatment to all classes of consumers; and, further, without such a tariff it is impossible to encourage the use of electricity to an extent which will give consumers the full advantage of the growing efficiency and low operating cost of the modern power station. Electricity legislation compels an undertaking to offer a tariff based upon a rate per Board of Trade unit, but permits an alternative method of charge by agreement with the consumer. A minimum standing charge is recoverable which is independent of the consumption. From the early days of electricity supply the difficulty of allocating standing charges in proportion to the units supplied has been appreciated, and it is permissible by agreement to construct any non-preferential tariff that fairly allocates the standing and running charges to each class of consumer. The information contained in the paper inclines me to the opinion that the majority of the costs incurred can only be handed on to the consumer by some method of assessment; they cannot be proportioned to the registration of electrical measuring instruments. I understand that the authors consider that the proper proportion of standing and running costs can be handed on by means of a graded unit charge. I would hesitate before agreeing to this as a principle, though there are arguments in its favour, the principal one being expediency. Whatever the form of the tariff, I am of opinion that it should take care of the following three items: (*a*) A charge per consumer. (*b*) A charge per kW or per kVA. (*c*) A charge per unit to cover production and transmission losses. The charge per consumer should be only large enough to ensure that the large number of small consumers are paying a proper proportion of service, meter, and office-administration costs. This charge per consumer does not require grading. The relation between large and small consumers' costs should be included in the kVA or kW charges. These should be fairly steeply graded according to quantity, because, as the authors point out, distribution costs do not increase in anything like the same proportion as the kW or kVA transmitted. The cost per unit does not appear to call for grading, but on the score of expediency it would be better to grade it in order to encourage additional consumption. The information contained in the graphs shown in Appendix VI is particularly useful. They enable one to visualize the remarkable diversity factors applicable to various classes of loads, and include information which the smaller undertakings would find difficulty in obtaining.

Mr. R. H. Scotson: I should like to draw the authors' attention to Fig. 4, which shows the load due to a Council house having an annual consumption of 900 units with a connected load consisting of lighting, cooking, heating, wash boiler, kettle, and water heater. Fig. 7, on the other hand, shows an annual consumption of 750 units for lighting and small appliances only. The additional revenue in the first case does not justify the heavy capital expenditure on cooking, heating, wash boilers, and water heaters, for Council houses. Referring to tariffs, in order that supply authorities might safely develop loads other than lighting it would be advantageous in some cases to buy electricity at two rates. A supply authority can afford to pay more for units to be sold as lighting than it can for units to be sold for other purposes, because, unlike other applications, electricity for lighting has no serious competitor.

Mr. A. H. W. Marshall: It would be of interest to know how the authors deal with capital expenditure which has to be incurred in advance of the load, and which usually varies considerably from year to year. Do they allow an average increment each year in a growing undertaking? In reference to the acquisition of low-priced load, I take it that the objection they offer to the utilization of spare plant capacity for this purpose does not apply to off-peak load, and that some remission of standing charges would be admissible in this case. In the apportionment of generating costs between standing and running charges, the ratio for current purchased is much higher on the standing portion. Why should this be so? If a grid tariff is intended, such a tariff would surely be based on the generating costs. I notice that the annual payment which will now appear in the balance sheets of all undertakings in respect of the frequency levy is not included in the analysis, and is apparently incapable of assimilation.

[The authors' reply to this discussion will be found on page 905.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 12TH APRIL, 1932.

Mr. W. E. Swale: In the past, tariffs sufficiently accurate to give reasonably good commercial results have been built up on a quite rudimentary cost analysis, modified and adapted by considerations of "service rendered" to the users and their "ability to pay." The need for a system as complex as that described in the paper is probably a function of the size of the area served. There is a more insistent need for an elaborate costing system in a widely-spread undertaking involving great rural areas than in an extremely compact one. In the undertaking with which the authors are associated the cost analysis is apparently the routine work of the statistical department, an organ of administration which in most undertakings is conspicuous by its absence. Is the statistical department responsible purely for the figures and records needed for the cost analysis, or does it also prepare and co-ordinate the many other records regarding system losses, total load connections, and consumers' characteristics? A central statistical department, run by a trained staff on modern lines, would be of great value to many branches of the activities of a large undertaking. The supposed heavy cost of such a department is usually the main reason for its absence, although if the total annual costs given on pages 870 and 871 are relatively correct only 1·12 per cent of the total expenditure is devoted to the statistical department. The cost of the department is thus very small indeed, in view of the exceedingly valuable work which it does. With regard to the question of definitions, although the precise meanings of the terms "diversity factor," "effective demand," and "efficiency factor," are fairly clear when the paper is studied, so many alternative readings are found in the literature of the subject that it would be valuable if the authors could add a small appendix to their paper defining all the terms about which ambiguity may exist. Referring to Table 8, it would be interesting to know exactly what "kW of power connected" means. Is the total horse-power connected merely multiplied by 0·746, to convert it to kilowatts, or is allowance made for the motor efficiency? I hope that the time will soon come when the use of the horse-power as a unit will disappear entirely, and motors will be rated according to the number of kW which they actually take. Turning to the statement (page 853) that "The expression 'overhead costs' used later in the paper is exclusive of capital charges," the authors make no mention of such capital charges as income tax, interest on shareholders' capital, and a sinking fund to meet depreciation. Are these important items dealt with separately by the accounts department? How are these charges allocated to the three groups of consumers? The crucial point of the whole analysis is surely the allocation of capital expenditure at the bottom of page 871. What are the authors' reasons for allocating 8·8, 63·33, and 27·87 per cent respectively of the cost of generating stations to Groups A, B, and C? Have they found it possible by means of load models or summation load-curves to get a close approximation to the true peak-load responsibility? I should like to know how the figure of £127·6 for the expenditure on one point of supply (page 890) was ascertained. The figure of 9·5 per cent for the percentage return on total capital involved clearly has to be sufficient to cover the capital charges previously mentioned.

Mr. O. Howarth: The paper shows that a correct analysis of costs depends very largely upon good judgment based upon experience. For instance, the correct determination of the diversity factor for the various classes of consumers must be largely a matter of judgment and is not capable of very accurate measurement. It must also be borne in mind that if adding the consumers' demands and dividing by the station demands gives a diversity factor of 1·1, where there is a 10 per cent loss between the station and the consumer the real consumers' diversity factor is 1·22. Consideration therefore has to be given to the question of which diversity factor to use. An examination of the appendices to the paper shows that the undertaking sells at a lower kW charge than cost, and recovers the difference from the unit charge. Assuming that the figures given in Appendix IV are typical values, I have worked out the costs of supplying a cotton mill on the basis of a 27 per cent load factor, a maximum demand of 1 000 kW, and a 9 per cent allowance for depreciation and interest on capital. The average economic price works out at 0·70d. per unit. For a 250-kW cotton mill working full time the economic price would be 0·753d.; on short time the price would be higher. Turning to Fig. 4, the low value of the base load shows that in the Council houses referred to little use is made of electricity for heating purposes. This curve shows a load factor of 42 per cent. If electric heating were used continuously in some of the rooms of these houses the diversity factor would probably be considerably less. On examining the diversity factor and load conditions in a house where electricity is used continuously for heating I found that the load was 3·75 kW at the time of high-voltage peak and 5·8 kW at the time of low-voltage peak. The total kWh were just over 11 000 per annum. Taking a diversity factor of 4, on the basis of Appendix IV the total cost works out at £16·1 per annum, and the total annual revenue under a local tariff would be £28·1, giving a return of 8 per cent on the capital. In connection with the church-hall heating installation dealt with in Fig. 20, the load is approximately 4 kW on high-voltage peak, and 16 kW on low-voltage peak; assuming a diversity factor of 2 on low-voltage peak loads, on the basis of Appendix IV the economic cost amounts to 1·7d. per unit, allowing 9 per cent for depreciation and interest. I am acquainted with some premises equipped with tubular heating which is left on continuously and where the consumption is about 10 times that of the installation considered in Fig. 20. I worked out the cost in that case assuming they were one-tenth the size. The annual load factor based on the highest demand for the year is 35·6 per cent, and the units consumed are 10 900. The maximum load is 3·5 kW on low-voltage peak and 3·1 kW on high-voltage peak. Assuming no diversity between groups of consumers of this type, the economic price works out at 0·86d. per unit—rather less than half

that of the installation dealt with in Fig. 20. This example shows that with continuous heating a much better load factor is obtained, and it is worthy of note that for this system of heating the economic price is only half that of electricity for intermittent heating. With continuous heating the consumption will clearly not be nearly double that with intermittent heating, probably not 20 per cent more, so that continuous heating is apparently a much better proposition for both the supply undertaking and the user. With continuous heating there is little or no diversity, and the difficulty of judging the diversity factor therefore disappears. With regard to demand charges, sometimes the annual demand is taken, and nowadays the statutory demands under the 1926 Act are becoming rather popular with suppliers, but not with users: sometimes the monthly maximum demand is taken. The authors do not indicate which demands they really refer to in their curves. Under the 1926 Act the price of bulk supplies given by an authorized undertaker to another authorized undertaker allows for transmission costs, and therefore the distance from the station has a considerable influence on the cost of supply to a particular consumer. This rather upsets the authors' analysis, because it prevents us from averaging out the costs of supplying consumers at widely different distances from the station. The route from the point of supply to the point where the supply is given to the other authorized undertaking must be considered. I should like the authors to explain how they deal with the opening-up of new areas which do not become profitable for many years. Do they recommend that in order to cover development expenses the charges to all consumers should be increased? Although the existing consumers may complain that it is unfair that they should be penalized in order to help new consumers, they ought to bear in mind that they themselves were originally given a supply at the expense either of some other consumer or of the shareholders or ratepayers.

Mr. J. L. Carr: Although on page 857 the authors refer to the actual maximum demand in assessing costs, in the preparation of some of the schedules they appear to base their estimate of cost on this value, instead of working on an equivalent demand derived from the actual maximum demand with due regard to the magnitude and the incidence of the latter with reference to the main load. The fixed costs of a distribution system supplying essentially one type of load, as, for example, in a residential area, are directly proportional to the diversified demand, but the equivalent-demand method should be used to determine the fixed costs of the generation and main transmission systems. No load should be developed at an extremely low rate which would, in the final state of development, prove uneconomic. The equivalent-demand method is of considerable value in enabling one to form some idea of the economic limit when any particular load is fully developed. The important effect of temperature has been disregarded in some of the authors' load curves for domestic users. The day load in a domestic area will vary very considerably with temperature, and a difference of 15 to 20 deg. F. may be accompanied by a 2:1 variation in load where extensive heating is installed. The effect of heating is very important as regards domestic consumers, as is shown by the following figures taken from the paper. In Fig. 4, which refers to a small all-electric house where little heating equipment is installed, the daily use is represented by 13·1 kWh per kW of demand. In Fig. 9, again for a house in which little heating is installed, the figure exceeds 10 kWh per kW demand; whereas in Fig. 11, for a house where a more extensive heating equipment is installed, the use falls to approximately 9 kWh per kW supply. The curves presumably refer to winter days, with similar temperature conditions, and the values given indicate that the daily load factor is reduced with increased heating. In the case of the annual load factor, however, the difference would be very much more marked because in the summer months the heating load would practically disappear, whereas the load due to the cooker and miscellaneous appliances—lighting may be ignored for all practical purposes—would still be of importance. The particulars given of domestic consumption indicate that the group demand factor is appreciably lower than that for similar users in this area. The authors suggest that in most cases full use is not made of the service provided, and this may be due to the adoption of a higher running charge than is usual in this area. The effect of a comparatively high running charge is to discourage the use of electricity for general heating, and, as such electric heating in small houses is usually provided by means of radiators, to reduce the maximum demand. This consideration probably accounts for the reduced demand factor referred to previously. If, therefore, after the actual cost of supplying a load of ascertained characteristics has been considered an economic tariff is introduced in which the running charge is low, the result may be to encourage some particular use (e.g. heating appliances) which will ultimately alter the characteristics of the load. In other words, load and tariff cannot be considered independently, and due regard should be paid to this important point when arranging tariffs, particularly for conditions of partial development.

Mr. H. Shackleton: From the fourth paragraph on page 861 I gather that the authors suggest the figure of 1·4 as the diversity factor between all distribution substations, 1·2 being the average diversity factor at a point somewhere between the generating station and the distribution substations. Investigations made by a large supply undertaking in this district showed the diversity factor between 82 6·6-kV mains, each of which supplied a distribution substation, to be 1·21. The diversity factor between the 6·6-kV mains fed from each transformer at the main step-down stations was 1·07, and between these transformers 1·15. The apparent discrepancy between 1·21 and 1·07 × 1·15 (= 1·23) was due to the fact that the former figure (1·21) included certain 6·6-kV mains which gave supply direct from generators, without any intervening transformers. I suggest that the large diversity factors obtained by the undertaking with which the authors are associated are made possible by the large area of supply and the immense variety of load obtained. The advantage from the supply authority's point of view of having one coal fire per house is shown to some extent by a comparison of Figs. 4 and 11. The consumption during winter months is very low (3·15 kW per day) for consumers

with a coal fire, compared with 36 kW per day for those without a coal fire. I am unable to agree that with the addition of a comparatively small amount of heating and cooking, the morning load in houses exceeds the evening load. Comparing Figs. 7 and 9, we see that the addition of a fairly large amount of cooking per consumer does not increase the morning peak, but on the other hand the evening peak in Fig. 9 is less than half that in Fig. 7, although the lighting connections have only been reduced by 40 per cent and other connections have been increased by almost 200 per cent. Records taken at distribution substations in certain residential areas near Manchester show that in 50 per cent of the cases examined the substation peak occurred in the evening, although in these areas the connected heating load ranged from 36·3 to 43 per cent and the cooking load from 30 to 40 per cent of the total connected load. The figures given in the table at the foot of page 869 indicate that the annual load factor of Group C consumers, based on maximum demand at the power station, is 18·4 per cent. This value, which takes into account diversity between substations, is surprisingly low. The demand factors of domestic consumers on the North-East Coast appear to be considerably lower and the consumptions very much higher than those experienced in this locality, and yet the annual load factor for Group C consumers in this district is of the order of 25 per cent, i.e. approximately 36 per cent greater than the authors' figure. Perhaps they will explain this. I am pleased to see their suggestion for improving a two-part tariff for domestic supplies by the substitution of a sliding-scale unit rate for the single unit charge. The suggested modification should be designed to remove the present anomaly that it is possible for large domestic consumers to obtain energy at rates comparable with those charged for high-voltage supplies. In my opinion the average load curves illustrated in the paper do not provide the best basis for assessment of costs of supply. The additional load demanded during very cold spells would only affect these curves to a small extent. Generating plant and mains must be capable of dealing with this abnormal load, and the capital charges on the additional equipment must be met. If the supply authority shows a profit with tariffs designed on the basis of the present paper, someone must have shouldered this extra burden. Apparently it would be divided between consumers in proportion to their average demands, in which case those with large amounts of heating load would not bear their fair proportion of the costs.

Mr. A. Fuchs: I should like to refer to a device I came across in Amsterdam which would considerably help to flatten the load curves of generating stations. This device supplies hot water for domestic use. It consists essentially of a heat-insulated cylinder, and no matter how much water is kept in the cylinder it is always maintained at a definite temperature. The water supply may be cut off and the contents of the cylinder used up as required. When the supply is restored the water fed into the tank also enters at the correct temperature. A synchronous-clock switch worked from the standardized supply frequency switches a cheap-rate electric supply on to the cylinder when the load is below the normal value (e.g. during the dinner hour), and switches it off at the commencement of the high-load periods. By choosing the correct size of cylinder one can heat sufficient water during the night and the dinner hour to meet the requirements of the day, and the heat-insulating jacket keeps it hot. Should the hot water be used up before the clock switch restores the cheap electric supply, however, the water heater can be manually switched over to the normal house supply (at a higher tariff) until sufficient hot water has been obtained or until the clock switch restores the cheap supply. I should very much like to know whether the authors have considered this device, or whether they do not deem it worth encouraging in their particular districts.

Mr. W. Fennell: In Fig. 11 the authors give a load curve for a small house having 6 kW of heating and 5·8 kW of cooking where the maximum demand is 2·5 kW. In my opinion such a low figure as this would be impossible for any one house, though if there were 20 or 30 such houses one might get an average figure of this order. I should like to see a curve for a house of slightly larger type where late dinner is the rule, because I am sure that it would show a much greater evening load. There are districts in my area where the maximum load occurs between 7 p.m. and 8 p.m. In addition to cooking apparatus, electric radiators would be in use in the living room, or the billiard room, which would bring the maximum load to about 15 kW. With regard to the addition of a sliding-scale unit charge to the two-part tariff, I have been successfully operating such a schedule for a considerable number of years. The first 100 units per quarter are charged at 2d. per unit, the next 100 at 1d. per unit, and the remainder at $\frac{3}{4}$d. per unit. One disadvantage of the scheme is that it prevents the smaller consumers from using cheap electricity for incidental work such as is done by wash boilers, breakfast cookers, and electric irons. They cannot afford to get beyond the high rate of the first 100 or 200 units, and are therefore purely lighting consumers. This type of tariff therefore prohibits the kind of load one ought to encourage, especially in connection with housing schemes. I think the paper would be improved if all mention of generation were omitted, as almost before we can adopt any of the methods recommended in it we shall be buying electricity in bulk. Starting on a basis of £a per kVA + bd. per unit for bulk charges, one can build up a corresponding schedule of detail charges much more simply than the authors have done. Turning to the estimate on pages 890 to 892, I find that the estimated net revenue is £119 15s. 2d. for the new consumers, but the schedule does not state the figure actually obtained. It would be interesting if the authors could quote an estimate of 2 years ago and compare it with the result being obtained to-day. Their estimates and results balance almost to a halfpenny; I cannot obtain such close agreement, though fortunately the results are usually better than the estimates. It is suggested in the paper that we should not develop loads which depend upon the precise time of the peak tallying with that of some characteristic of the station or supply load for the area. I think a good many of those of us who buy in bulk find that this is almost the only way in which we can develop any considerable power load. If a consumer can be obtained who will consider an

off-peak basis, I think we should encourage it, otherwise the addition of the kVA charge will probably produce such a high average unit charge that no business will result. I have accepted a number of consumers on agreements in which use during certain hours is not allowed, or must be reduced substantially. In other words, in order to obtain a very low power cost the consumer must be careful to arrange his work so as to avoid use during those hours of maximum demand during which the bulk kW charge is decided. If the times of station maximum demand do vary and clash with some of these agreements later on, all that one can do is to approach the consumers and ask them to alter their hours. If they will not do so, the agreement must run its course (usually not a very long one), and when it is renewed the prices must be raised in relation to those charged to others who are willing to keep clear of the period of peak load.

(*Communicated*): With regard to peak loads, the present increase in the domestic load is causing the bulk-supply peak to occur later in the evening; whereas it used to be at about 4.30 p.m. it now comes on much later—say at 7 p.m., when the industrial loads are shut down. It is therefore becoming easier year by year for the owners of works operating during normal hours to sign, and less risky for the supply authorities to accept, "off-peak" agreements.

The Authors' Reply to the Discussions at London, Birmingham, Newcastle, and Manchester.

Major E. H. E. Woodward and **Mr. W. A. Carne** (*in reply*): We propose to classify our replies to the contributions of the various speakers according to the subject matter of their remarks.

Object and Method of Analysis.

Mr. Purse questions whether there is any advantage to be obtained from a detailed analysis of costs. The object of the analysis is to eliminate the necessity of making broad assumptions, and to reduce the problem under review to a multitude of small items, to some of which there is a direct answer and to the remainder of which narrower and more accurate assumptions can be applied. By this method much more accurate results can be obtained than by the "usual and simpler" methods advocated by Mr. Purse. Moreover, the person performing such an analysis is in possession of knowledge of the real meaning of such figures as he has obtained and of their limitations of application to practical problems, and is in consequence less liable to be led to false conclusions.

An important function of an analysis formula is to enable costs to be predicted for conditions of load, numbers of consumers, etc., differing from those obtaining during the costing period, and Mr. Perks suggests that more attention might be given to future conditions. Under stable (but not necessarily stationary) conditions an analysis system based on sound principles should produce almost identical formulæ year after year, changing only gradually as greater efficiency in some direction is attained; any considerable and sudden variation in the figures should reveal some flaw in the system. Actually, however, the figures, more particularly those relating to capital, are affected from year to year by various causes, such as fluctuations in output due to the condition of trade, and the establishment of new generating stations or other works, involving heavy capital expenditure, which must remain partially undeveloped for some years.

Although in the paper a complete analysis of assumed costs for a particular year is given and the results are applied directly to the solution of problems, we have in practice found it advisable, after making an analysis of the actual costs of any year, to make a second analysis using the actual cost figures for the year as a basis, but adjusting them where necessary to compensate for any abnormal conditions; it is on the formulæ obtained from the second analysis that problems are worked out.

Limits of Accuracy.

The practice of working to five places of decimals is criticized as being out of keeping with the general limits of accuracy of the analysis. It is done to enable each section of the analysis, and finally the totals, to be balanced by cross-multiplication and thus to avoid the introduction of possible errors due to misplacement of decimals, inversion of numbers, and similar mistakes which are liable to be repeated during checking.

Inclusion of Generation Costs.

Mr. Fennell and Mr. Purse both suggest that an analysis of generation costs is no longer necessary, as supply undertakings will shortly be supplied by the Central Electricity Board on the "grid" tariff. It must, however, be remembered that provision is made for station owners in certain instances to obtain their requirements at adjusted station costs, and in any case so long as generating stations are provided and run by supply undertakings a knowledge of generating costs will be of importance to them. It is also inevitable that, in course of time, changes in fuel and design of plant will take place which will necessitate revision of the formulæ contained in the regulations as to allocation of cost of production, and it will be desirable that station owners should be able to assist in the consideration of the formulæ, as they have done in the past.

Tariffs.

Points relating to tariffs are raised by many speakers. In several instances it is assumed that cost analysis will tend to make tariffs more complicated, and in a few cases the formulæ derived from the analysis appear to be looked upon as proposed forms of tariffs, although we endeavoured to make it clear in the paper that this is not so.

The use of a system of cost analysis does not carry with it any necessity to make tariffs complicated or to adopt tariffs which will ensure the same return on capital in all cases. In this connection Mr. Purse accuses us of inconsistency, and quotes certain passages in support

of this charge; we do not agree that there is any inconsistency in our statements if the passages are read in their proper context. As stated, the object of the analysis is to debit each class of supply with its proper proportion of every cost, but this does not mean that it is practicable or desirable to adhere rigidly to this principle in designing tariffs.

In our view a knowledge of cost principles is often of assistance in simplifying and standardizing tariffs. With some classes of load very simple tariffs will, within the limits of the particular conditions associated with such loads, produce revenue reasonably close to that which cost analysis shows to be required. For instance, for average colliery supplies a tariff with different unit rates for current taken during day hours on weekdays and for current taken at night-time and week-ends, with some grading for quantity but no charge in respect of demand, appears to follow cost quite reasonably. Clearly, such a tariff is entirely different in form from the formulæ obtained from cost analysis.

Mr. Digby refers to the tariff used on page 890 in the specimen Form 1, but we did not intend its use there to be taken as a recommendation for its general adoption. It was used merely to fill in with figures the spaces provided in the form for various charges.

In aiming for simplicity in tariffs it is necessary to distinguish between simplicity from the point of view of the consumer and from the point of view of the supplier. There is no real objection to a considerable number of tariffs, and, as Sir Arnold Gridley points out, there are sometimes advantages in alternative tariffs.

The supplier, with his special knowledge, is able to cope with whatever difficulties a variety of tariffs introduces on his side. The consumer requires a tariff which is simple and easily understood when applied to his particular case, and this is more readily obtained by the adoption of a reasonable number of different tariffs for various uses or classes of consumers than by attempting to find one all-embracing tariff. Even a tariff for one class of consumer may appear complicated as a whole and yet meet the requirements of simplicity when applied to a particular consumer. For instance, the domestic tariff adopted by the North-Eastern Electric Supply Co. is a sliding-scale tariff of the form shown in Table C.

At first sight this system appears somewhat complicated, but an individual consumer is only affected by one line of the table and he has a scale of charges in a form which he easily understands and one which acts on a principle very generally recognized in buying, namely a reduction in price with quantity.

As pointed out by Sir Arnold Gridley and Mr. Hobson, a knowledge of cost principles is important when designing tariffs, but other knowledge is necessary. There are also required experience and common sense, a knowledge of the business to be supplied, a grasp of practical considerations such as metering, ability to visualize future conditions, and, above all, an understanding of the consumer's point of view.

TABLE C.

Number of assessable rooms	Units per quarter at (*1st rate*) per Board of Trade unit				Next units per quarter at (*2nd rate*) per Board of Trade unit				Next units per quarter at (*3rd rate*) per Board of Trade unit				
	Mar.	June.	Sept.	Dec.	Mar.	June	Sept.	Dec.	Mar.	June	Sept.	Dec.	
4 or less	32	16	16	32	26	13	13	26	500	250	250	500	All in excess at (*4th rate*) per Board of Trade unit
5	38	19	19	38	30	15	15	30	550	275	275	550	
6	50	25	25	50	40	20	20	40	600	300	300	600	
7	64	32	32	64	52	26	26	52	650	325	325	650	
8	82	41	41	82	66	33	33	66	700	350	350	700	
9	102	51	51	102	82	41	41	82	750	375	375	750	
10	122	61	61	122	98	49	49	98	750	375	375	750	
11	142	71	71	142	114	57	57	114	750	375	375	750	
12	162	81	81	162	130	65	65	130	750	375	375	750	
13	182	91	91	182	146	73	73	146	750	375	375	750	
14	202	101	101	202	162	81	81	162	750	375	375	750	
15 or more	222	111	111	222	178	89	89	178	750	375	375	750	

Mr. Bolton, Mr. Bernard, and Mr. Blaikie, refer to the question of variation in the charge per unit included in any two-part tariff, and the question is also raised why there should be any reason for such a variation in the case of supplies for domestic purposes or shops. If it is correct to express costs as a cost per consumer, a cost depending on demand, and a cost per unit, a theoretical tariff would have to include a charge in respect of demand, besides a fixed charge and a unit charge. In a two-part tariff containing only a unit charge and a fixed charge depending on rateable value, number of rooms, floor area, or some such factor, the fixed charge can be chosen so as to cover the cost per consumer plus the demand cost equivalent to some assumed demand. The actual effective demand is not, however, a constant for a consumer with any particular size of house or shop, but increases with the consumption—though not usually proportionately. It is not practicable to arrange for the fixed charge to correspond to the highest demand which may be made, as if this were done a smaller user would be unduly penalized. The fixed charge must therefore

usually be so chosen as to cover only the demand likely to be made by a comparatively small user, and the additional costs entailed by an increase in demand must be recovered from the unit charge. The amount to be added to the theoretical cost per unit on this account is naturally dependent on the increase in the effective demand entailed by increase in consumption.

For shop lighting the increase in demand for a given increase in consumption differs from the increase in demand for a similar increase in consumption in the case of general domestic supplies; and in the case of domestic supplies the earlier increases in consumption, such as are brought about by a higher standard of lighting, usually bring with them greater increases in effective demand than increases further along the scale, which usually correspond to load used to a considerable extent when other load is low.

Capital Expenditure.

Mr. Sayers, Mr. Cooper, Mr. Bolton, and Mr. Salt, refer to the manner in which capital expenditure is dealt with, that is by leaving it in the form of the amount of capital expenditure per kW (or per kVA) and per consumer, instead of resolving it further into an annual charge to cover interest and depreciation. There is, of course, no difficulty in adding a further column to the sheets of the analysis which deal with capital expenditure and expressing each item as an annual charge, taking such rates for interest and depreciation as may be appropriate to it. We have found, however, that in most applications of the analysis the figure required is the amount of expenditure, and the analysis was therefore left in this form, the further calculation being made when required. Where the figures derived from analysis are used for the purpose of deciding whether a particular supply is profitable, we think that a figure representing the percentage return on the capital expenditure involved generally gives a clearer picture of the position than one which shows the profit or loss remaining after allowing for interest and depreciation charges at certain rates. We agree, however, that this is merely a question of individual preference, and that from the point of view of a municipal undertaking the other method may be more useful.

In reply to Mr. Marshall, undeveloped capital expenditure is included in the capital figure in the analysis because the charges on this have to be met. Where the amount of such expenditure exceeds normal, however, an adjustment is made as explained on page 905.

Depreciation Charges.

We have studied Mr. Cooper's contribution to the discussion with much interest, particularly his remarks dealing with depreciation. He is among those who criticize our method of expressing profit as a return on capital expenditure. We are in agreement with his remarks to the extent that this method only indicates whether a supply is profitable or not, provided knowledge is available of the percentage required to meet depreciation charges in each case. We are, however, very doubtful as to the accuracy with which such percentages can be obtained by the adoption of assumed lives for different assets, in view of the many varying and uncertain factors which bear on the subject; we are inclined to the view that for practical purposes it is more satisfactory to take an overall figure based on past experience of the provision which it has actually been found desirable to make.

Power Factor.

Mr. Bolton suggests that the expenditure on generating stations should be divided between those parts which are influenced by power factor and those which are not. We are in agreement with this, and consider that the analysis could be improved by taking account of power factor in each step of the process of analysis. It would not be difficult to extend the analysis to take account of power factor at times of maximum load, but it would be less easy to allow for the effects of power factor on generating efficiency at other times.

Mr. Minshull asks whether we have come to any definite conclusion as to the most satisfactory method of inducing consumers to take their supply at a reasonably high power factor. In our experience the only way of doing so is by an adjustment in price depending on power factor; but we are unable to recommend any particular method of adjustment which is applicable to both two-part and flat-rate tariffs and is satisfactory under all conditions.

Losses.

Mr. Sayers's contribution to the discussion, and also his paper on "Electricity Supply Tariffs,"* give an able and comprehensive view of the involved subject of losses. He rightly points out that by dividing the generating running costs by the units sold the true cost per unit at the generating station is not obtained, and he advocates charging the cost of generating units lost in transmission as a transmission cost. We are not unmindful of the points he raises, and we have in the past compiled an analysis of costs in such a way that the costs per unit and per kW were built up step by step from generation through high-voltage transmission and low-voltage distribution to the consumers' terminals. This analysis proved instructive, but extremely inconvenient to use in practice. For the purposes for which the analysis is required, the method of dealing with losses by using units delivered as the divisor is convenient and makes allowance for the average losses for each group. The whole question of losses is connected with power factor and "form factor," and their allocation between different consumers supplied over common cables is very complicated unless the principle of averaging is accepted. As an example of the simplest case, consider a new consumer requiring a load of x amperes over a cable already loaded to y amperes; the copper losses involved in supplying this consumer will be proportional to $(x + y)^2 - y^2$, i.e. to $x^2 + 2xy$; thus the losses allocated against this consumer include a proportion of losses dependent on the load already taken by other consumers. If, on the other hand, the losses are to be divided amongst the consumers, then the addition of every new consumer will require an increase in the losses allocated to the already-existing consumers supplied over the same cable. We therefore advocate working to averages for general

* *Journal I.E.E.*, 1925, vol. 63, p. 850.

problems, and only in special cases considering the problem in detail.

Diversity.

We agree with Mr. Swale that there is a possibility of confusion unless a definition is given of what is meant by diversity factor. The diversity factor to which we referred in the paper is the one most commonly used in this country and is the sum of the individual loads divided by the resultant load. There are other systems in use, notably on the Continent, where a factor is arrived at in an entirely different manner. As stated in the paper, the question of losses must be taken into consideration either by means of a separate efficiency factor, or, where convenient, by a combined factor taking account of diversity and efficiency.

Mr. Rissik asks how diversity factor is taken into account in arriving at the effective demands. In the case of the Group C consumers the method used is to determine what is called in the paper "the effective demand" for each type of consumer in this class. This demand is obtained by superimposing individual load curves as explained in Appendix VII, and from the resultant curve determining the effect of the load under review on the maximum loads on the low-voltage distribution network and the high-voltage system respectively. The effective demands thus take account of diversity, and as the method is equivalent to the employment of a separately-ascertained diversity factor for each different type of consumer, it avoids the necessity of using average and arbitrary values.

Mr. Rissik also inquires as to the method of obtaining the following figures for the kW demand on power stations due to each group, which appear in Appendix IV:—

Group A, 4 800; Group B, 34 500; Group C, 15 200; total, 54 500.

The total figure, of course, is known, and as the Group A load is made up of only a few consumers, each taking a steady load, it can be ascertained without undue labour. The Group C load is made up of a large number of low-voltage networks, and the maximum load of each during the winter months is known. The greater proportion of these networks can be allocated to one of the three following groups. (*a*) City networks, where offices, small power consumers, and main-street shops predominate, giving a load curve with a maximum between 3 p.m. and 5 p.m. and falling rapidly after 5 p.m. (*b*) Town networks, with a somewhat later peak—from 5 p.m. to 6 p.m. (*c*) Residential networks, where the maximum load is reached still later. For each of the groups (*a*), (*b*), and (*c*), typical load curves are available, and the average proportion of their individual maximum load which is incident on the power stations at the times of heavy load is known; their combined effective demand on the power stations can thus be calculated, after making an allowance for losses. Such networks as do not fall within any of the above groups are considered individually and their effective demand on the power stations is estimated. In this way a fairly accurate figure is obtained for the demand on power stations due to low-voltage networks. The demands due to Groups A and C having been arrived at, the demand due to Group B is obtained by subtraction. A comparison of this demand with the sum of Group B consumers' maximum demands enables an average diversity factor to be calculated for this group; due allowance must, of course, be made for losses in all the above calculations.

Although an average diversity factor for Group B consumers is of service in the consideration of general problems, such as predicting loads in different areas, it cannot be correctly applied to a particular type of consumer within the group. The diversity between Group B consumers is to a minor extent due to variations in shape of the daily load curve, and to a much greater extent to seasonal variations and to trade conditions which vary from year to year and detract from the value of any purely theoretical calculations of the diversity factors of such consumers.

Mr. Bolton suggests that the diversity varies inversely as the load factor, and that by a suitable transfer from the kW charge to the unit charge an allowance can be made for diversity; we referred to this on page 857, stating that "By choosing a suitable increase to the unit charge a reasonable corrective for the effect of varying diversity can be automatically obtained for a particular class of consumer, but the amount of increase so required varies with different classes." The latter half of this statement requires emphasis, as it is only between certain limits that the diversity varies inversely as the load factor. The curve shown in Fig. C gives an indication of the diversity that may be expected between power consumers with various load factors.

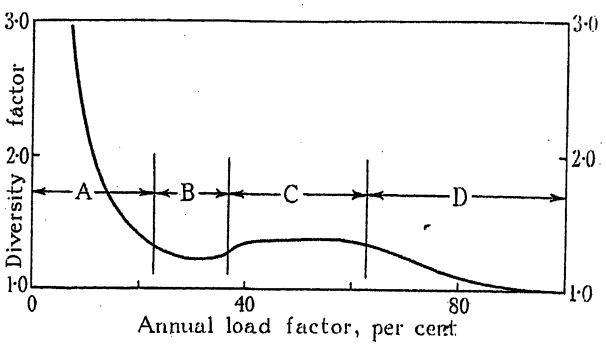


FIG. C.

As the load factor increases to 25 per cent or thereabouts the diversity falls rapidly. A load factor of 25 to 30 per cent represents manufacturers normally working a regular 8-hour day, the diversity between whom is comparatively small. Further along the scale come consumers working a greater number of hours per day, such as collieries (some with maximum demand at night-time), causing the diversity to become higher again before falling to unity at 100 per cent load factor. The logical outcome of this in relation to demand and unit tariffs is the provision of separate tariffs for consumers whose load factors fall respectively within the ranges A, B, C, and D, shown in Fig. C, the proportions of the total charge allocated to the demand and the unit parts respectively differing in each case. When the load factor is below 20 per cent or so, and the diversity is more or less inversely proportional to the load factor, the whole of the charge can be expressed as a charge per

unit within reasonable limits of accuracy. It was for this reason that we suggested that in the case of small power supplies from low-voltage networks a simple sliding-scale unit tariff was probably more correct from a cost point of view than a two-part tariff in which one of the charges is based on demand, kilowatts connected, rateable value, or some such factor.

Generation.

Mr. Blaikie suggests that it would be more correct to divide fuel into three parts: (*a*) a portion independent of either kW or units, (*b*) a portion varying with kW, and (*c*) a portion varying with units. He supports this with results obtained from Parsons lines, derived from his own observations, and suggests the formula

$$\text{Total cost of fuel} = A + (B \times \text{kW}) + (C \times \text{kWh})$$

We agree that this gives a more correct representation of actual conditions in any one station and is preferable to dividing fuel into two parts only, when considering problems relating to fuel consumption, the effect of variation of station load factor, etc. We suggest, however, that such a formula does not cover the case where growth of load necessitates the provision of additional generating stations, or the bringing into service of additional sections of a station. For instance, supposing the load (i.e. kW) to be doubled and the addition supplied by the provision of two such generating stations instead of one, the total cost of fuel would be $2[A + (B \times \text{kW}) + (C \times \text{kWh})]$. The constant A has now increased in the same proportion as the kW. In any case, for the purposes of cost analysis the fixed portion A has to be allocated to the groups on some basis, and the one adopted in the paper, i.e. respective demands, appears the most suitable.

Miscellaneous.

In addition to the subjects commented upon by several speakers and replied to above, various other points are raised.

Mr. Hobson asks for further details of the principles adopted in deciding whether a particular item of cost is to be allocated as per consumer or per kVA. In the first instance, the allocation is made on whatever appears the most logical basis. Some items of cost in respect of a particular group, such as the reading of meters, and the preparation of consumers' accounts, are clearly governed by the number of consumers within that group rather than by considerations of demand. The same is held to be true of the costs incurred in respect of the members of the staff, comprising what are referred to as the consumers' departments. For instance, the duties of certain members of the staff may be to attend exclusively to the smaller power consumers, and in this case the number of such staff required is closely dependent upon the number of consumers of this type. The costs of such staff are therefore allocated as a charge per consumer against this particular class of consumer. In other cases an item of cost may appear to depend to some extent, but not in its entirety, upon the number of consumers. In such cases the principle adopted by the authors is to subdivide the item into smaller components, continuing the process until each individual component can be logically allocated. From time to time an approximate check of the correctness of the allocation of a particular item can be made by comparing any increase in the total amount of the item with growth in number of consumers and growth in demand.

Mr. Sayers questions the correctness of allocating rates between the three main groups on the basis of the capital expenditure allocated to the groups. Our argument for doing so is that, in so far as rates are not dependent on capital values, they are approximately a function of profit, and, assuming an equal return on capital from each group, the profit will be proportional to the capital expenditure.

Mr. Cooper points out that interest on coal stocks is not shown in the example of the analysis, although reference is made earlier in the paper to its inclusion as a charge under generating costs. With a view to keeping the example within reasonable length, several items were not shown separately in it, but were incorporated with other similar items.

Mr. Bolton suggests that some small part of the distribution working expenses would be more correctly treated as a charge per unit, and we are inclined to agree with him in this. We do not, however agree that there is ground for accepting proportions similar to those used for generation (excluding fuel), and we consider that further investigation might be profitably directed to this point.

Mr. Rissik asks for further explanation of the expression "half diversity factor." What we meant was that the average diversity factor required for transmission is between unity and the diversity factor (say, D) at the consumers' end of the line. We therefore used a diversity factor equal to $\frac{1}{2}(1 + D)$.

Mr. Rissik also asks how in Table 8 it is possible for the effective demand on the low-voltage network to be higher than the effective demand on the high-voltage network. This position arises where supply is given from a low-voltage network on which the maximum demand occurs during the evening, and the average maximum demand of the supply in question occurs after the high-voltage-system load has fallen to a comparatively low value.

Mr. Hird suggests that the method of charging small consumers of the slot-meter type a fixed sum irrespective of consumption receives support from the figures derived from the analysis, as the cost of the additional consumption likely to be taken under such a method of charge would only be 0·208d. per unit. This is not correct, as an increase in consumption brings with it a decrease in diversity and an increase in effective demand. The cost of the increased consumption will therefore include the cost arising from an increase in the effective demand as well as the cost arising directly from increased units.

Mr. Sayer inquires as to the floor area of the premises dealt with in Figs. 3 to 11. We regret that we are unable to give these particulars, as a tariff based on floor area has not been employed in connection with houses by the undertaking with which we are associated, and figures of area are not available.

Mr. Rawll asks what type of domestic water-heater is used in the premises to which Fig. 11 relates. The

water heaters installed are of the hand-operated type incorporating a 3-heat switch, the maximum loading being 3 kW. The capacity of the tanks in question is 20 gallons, and the arrangements are such that alternative heating is provided by the kitchen fire.

Mr. Scotson draws attention to the comparatively small difference in annual consumption between the premises referred to in Figs. 4 and 7. It should be explained that Fig. 7 refers to a considerably larger type of house, where much more energy is used for lighting purposes, and the difference between the two consumptions does not give the consumption arising from the connection of cooking and heating load. It is apparent that the use made of the electrical equipment in the Fig. 4 houses is by no means full, but the curve is typical, being the average obtained from a considerable number of houses.

Mr. Swale asks whether the statistical department is responsible purely for the figures and records needed for the cost analysis. In the case of the undertaking with which we are associated this duty is only a small part of the work of the department, the activities of which extend in many other directions. In reply to his question regarding the expression " per kW of power connected " used in Table 8, the figures given are calculated on the basis of horse-power multiplied by 0·746.

THE ELECTRIFICATION OF THE SUBURBAN AND CERTAIN MAIN-LINE SECTIONS OF THE GREAT INDIAN PENINSULA RAILWAY.

By F. LYDALL, Member.

(*Paper first received* 11*th February and in final form* 14*th March*, 1932; *read at a Joint Meeting of* THE INSTITUTION *and the* INSTITUTE OF TRANSPORT 28*th April*, 1932.)

SUMMARY.

The paper gives a general account of the suburban and main-line electrification scheme on the Great Indian Peninsula Railway. The first portion sets out the circumstances under which the scheme was initiated, the principal reasons for the decision to electrify the surburban and the main-line services, the actual and anticipated traffic, and the general programme of carrying out the work.

The second portion deals with the local conditions which determined the design of a good deal of the plant and apparatus. This is followed by brief references to special points in the installation and design of the multiple-unit trains, electric locomotives, track equipment, bonding, substations, transmission system, power station, locomotive shops and car sheds, and system control. Such information as is available is given as to the capital cost of the complete scheme.

The last two sections contain a number of statistics of operation and notes of operating experience, and the paper concludes with an Appendix in which are given for reference the names of contractors and principal sub-contractors, and the technical particulars of the plant supplied and installed.

INTRODUCTION.

Descriptions have already been published of various elements of this electrification scheme, and a certain amount of general information has been given by the Press in notices of the official openings of the different stages. As, however, this electrification is second only in extent in the British Empire to that on the Southern Railway, and is in some ways the most comprehensive, it is thought that a general account of the scheme, with some comments on the various technical questions involved and a few particulars of operating experience, may be of interest in more than one direction.

A few figures will give an indication of the extent and general characteristics of the system.

Route mileage of track equipped	181·4 miles
Length of single track equipped, including sidings	571 miles
Number of suburban motor-coaches	53
Number of suburban trailer-coaches	153
Number of freight locomotives	41
Aggregate horse-power of freight locomotives	106 600 h.p.
Number of passenger locomotives	24
Aggregate horse-power of passenger locomotives	51 990 h.p.
Number of substations	15
Aggregate capacity of substation plant	100 000 kW
Length of 100 000-volt transmission lines	272 miles
Equipment of power station	4—10 000-kW sets
and	6—60 000-lb. boilers

Bombay, a city of about 1¼ million inhabitants, is situated mainly on Bombay Island, which contains in the south the Fort, now the principal business quarter, the higher-class residential area, the bazaars and the poorer-class quarters, and in the north the suburbs. Between Bombay Island and the mainland lies Salsette Island, which contains the more remote suburbs and a large undeveloped area (see Fig. 1).

Bombay is served by two railways, the Great Indian Peninsula and the Bombay, Baroda and Central India. Both deal with a heavy suburban traffic, consisting mainly of passengers travelling to the termini in the morning, and out to the northern part of the city and the surburbs in the evening, and with important long-distance passenger and goods traffic. The G.I.P. Railway provides a connection with Northern and Central India via the North-Eastern main line, and with Southern India via the South-Eastern main line. Both these lines have to negotiate the escarpment which runs roughly parallel to the coast about 40 miles inland, known as the Western Ghats, or, more usually in Bombay, the Ghats. This escarpment consists of a sudden rise from the coastal plain to a plateau about 2 000 ft. above sea-level. The Ghat section on the North-Eastern line is called the Thull Ghat, that on the South-Eastern line the Bhore Ghat. On both sections the ruling gradient is 1 in 37. The plan and profiles of the lines included in the scheme are shown in Figs. 1 and 2.

INITIATION OF SCHEME.

The initiation of this electrification development dates back to 1913, when a report was prepared by Messrs. Merz and McLellan on the application of electric traction to the suburban lines of the two railway companies, and to the lines of the Bombay Port Trust. This was followed in January 1914 by a report to the G.I.P. Railway Co. on the electrification of the main lines between Bombay and Igatpuri at the top of the Thull Ghat, and between Bombay and Poona, which includes the Bhore Ghat.

Before any action could be taken on these reports, the war put aside all such questions, but at the request of the G.I.P. Railway Co. a further report was prepared in 1919 which dealt not only with the suburban lines but also with the electrification of a considerable portion of

the North-Eastern main lines, comprising in all 1 023 route-miles. Following prolonged discussions between the Government of India, the Government of Bombay, and the Railway Co., sanction was given in August 1922 to the electrification of the harbour branch and the Mahim Chord (see Fig. 1) as a first instalment of the suburban scheme, and about a year later the conversion of the rest of the suburban zone, including the lines from Kurla to Kalyan, was approved. In February 1924 the consulting engineers presented another report containing a revision of the estimates relating to the main lines between Bombay and Igatpuri and Poona, on the basis of up-to-date statistics of traffic. These estimates were considered by the Railway Board under Sir Clement Hindley, the Chief Commissioner of Railways, on the application of the Railway Co., in the early part of 1925, and were forwarded in April to the Secretary of State with a recommendation that the scheme should be sanctioned. On the sanction being given, indents for the necessary plant (excluding the power station) were issued in December 1925, and for the power station in April 1926.

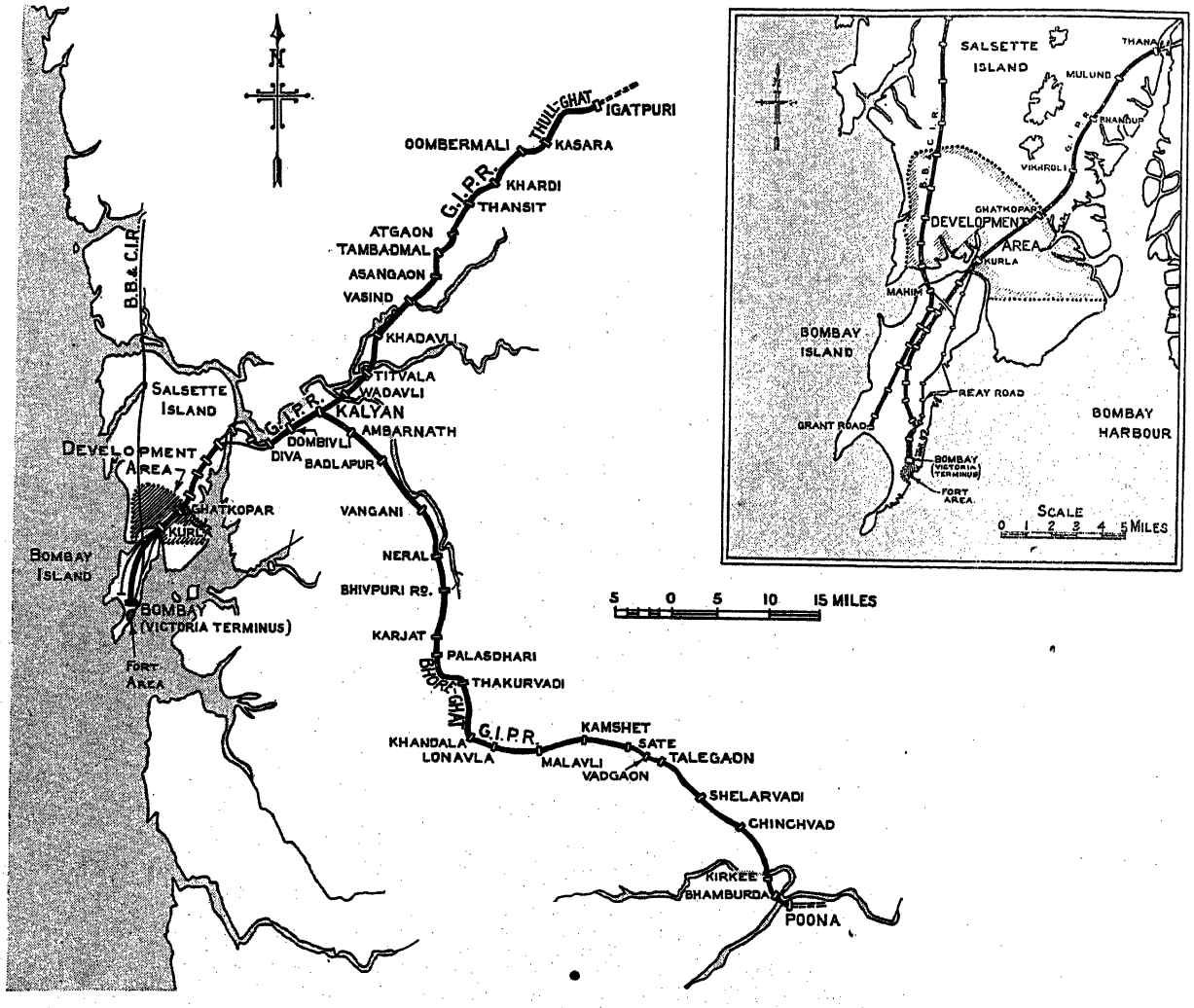


FIG. 1.—General plan of Bombay and district, showing lines included in the complete scheme.

COMPLETION DATES.

The opening of the first stage of the suburban electrification, coincident with the inauguration of the newly constructed extension of the harbour branch to the Victoria Terminus, was marked by an official ceremony on the 3rd February, 1925, attended by Sir Leslie Wilson, the Governor of Bombay, and Sir Clement Hindley, representing the Government of India. Succeeding stages were changed over from steam to electric working as the equipment of the line was ready, and the coaches were delivered. The electric service between Bombay and Poona was officially started by Sir Leslie Wilson's successor, Sir Frederick Sykes, on the 5th November, 1929, and a year later all traffic between Bombay and Igatpuri was taken over by electric locomotives, so that by the end of 1930 all steam working apart from that of a few shunting locomotives in the

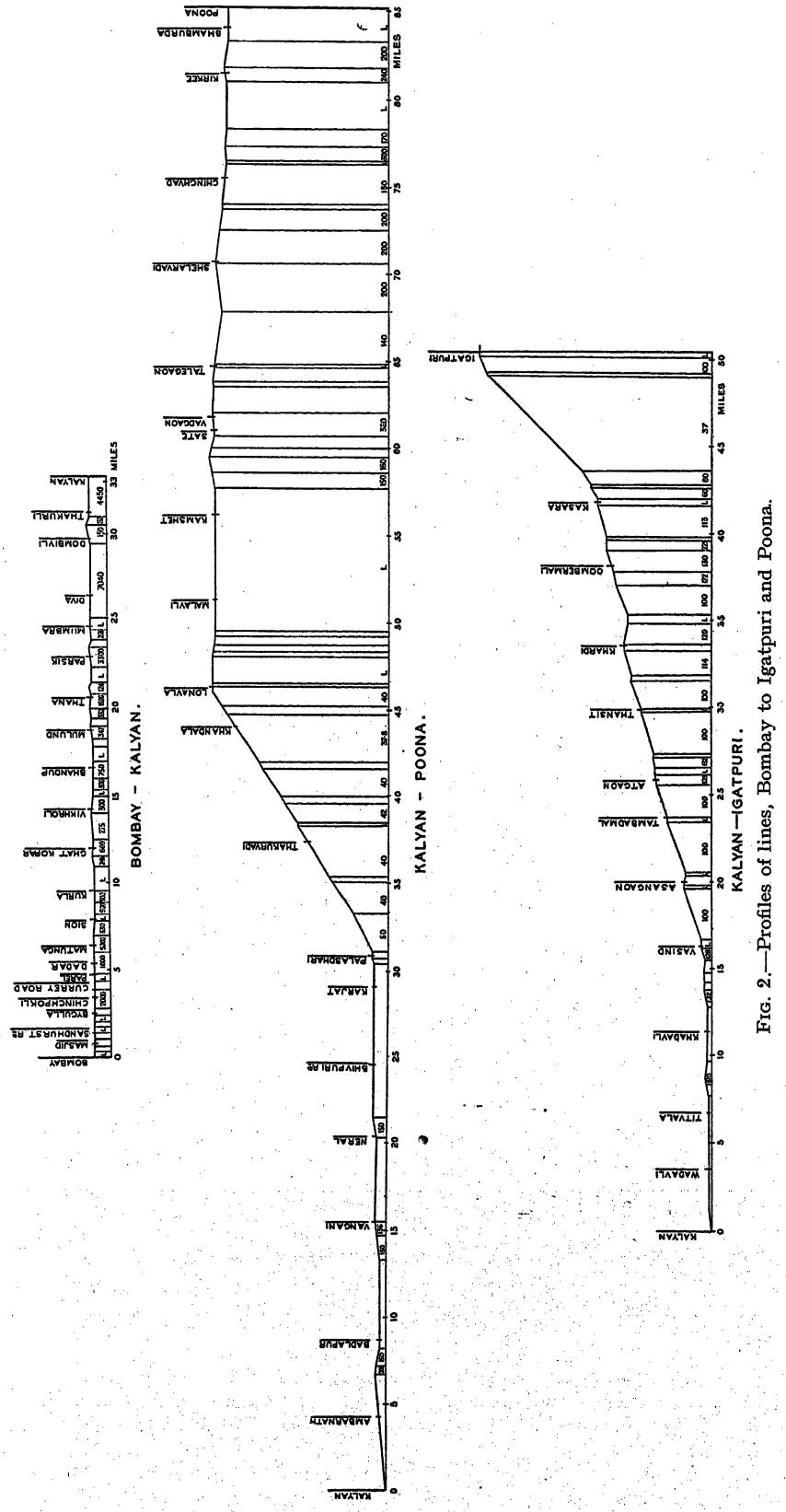


FIG. 2.—Profiles of lines, Bombay to Igatpuri and Poona.

goods yards and at Victoria Terminus, had been eliminated from the Bombay–Igatpuri–Poona sections.

Purpose of Electrification; Suburban and Main-Line Traffic.

As will be readily understood, the purpose in view in electrifying the suburban services was quite different from the object aimed at in converting the main lines. In the period immediately after the war the housing problem in Bombay was acute; rents in the city were high, and the sites for the erection of new dwellings limited. The Bombay Municipality, therefore, found it necessary to consider what steps could be taken to spread the population, and, amongst other schemes, decided to encourage the development of the suburbs, especially those in the south of Salsette Island. For this reason the proposal of the G.I.P. Railway to introduce electric working on their suburban lines was strongly supported by Sir George Lloyd (now Lord Lloyd), the Governor of Bombay, and by the Municipality.

Table 1.

Forecast of Traffic on Suburban Lines, excluding the Harbour Branch.

Date	Estimated total number of passengers to be carried daily	Estimated number in the two rush periods	Train mileage	Trains in each direction per hour during rush periods
1927	74 853	16 467	1 646 332	10
1932	103 388	22 745	2 121 015	15
1937	144 478	31 735	2 758 487	20

The first step was to construct a connection from the south end of the existing harbour branch at Reay Road to the terminus. This connection was only practicable by taking the new part of the line overhead on a series of masonry arches and steel viaducts until it crossed the main line 1½ miles north of the terminus. From this point the line descends by a curved gradient of 1 in 34 to join the main line. It was clearly impracticable to operate an intensive suburban traffic on gradients such as this by steam locomotives, and this was one of the reasons which led to the electrification of the whole of the suburban services.

It was estimated that by 1931, or shortly afterwards, 205 000 people would be housed on estates catered for by the harbour branch, and that a train service of at least 20 trains per hour during the morning and evening rush-hour periods would be necessary. For the suburban lines, excluding the harbour branch, estimates based on the normal increase in passengers during the previous five years plus the anticipated traffic from the development schemes, and on the assumption that 22 per cent of the passengers would be carried during the rush periods, gave the figures in Table 1.

Growth of Suburban Traffic since Electrification.

The figures in Table 2, taken from the annual reports of the Railway, show that although the traffic has increased, the rate of growth has not come up to expectations.

It may be of interest to consider the reasons for the growth of traffic being less than was anticipated. It is, of course, well known that India in general, and Bombay especially, have felt the effects of the world-wide trade depression; but even while other countries were doing well, Bombay was not, contrary to expectations, expanding its general volume of trade. This is shown by the statistics in Table 3.

Table 2.

Particulars of Suburban Traffic following Electrification.

Year	Harbour branch		Other suburban lines	All suburban lines
	Train-miles per day	Passengers	Passengers	Passengers
1st April, 1924, to 31st January, 1925	79	208 114	24 729 267	25 605 771
February and March 1925	421	668 390		
April 1925 to March 1926	740	4 844 244	23 408 268	28 252 512
April 1926 to March 1927	2 612	13 571 273	18 226 078	31 797 351
April 1927 to March 1928	2 787	18 434 421	14 585 849	33 020 270
April 1928 to March 1929	1 945	17 305 806	14 191 410	31 497 216
April 1929 to March 1930	2 335	17 878 967	15 045 428	32 924 395
April 1930 to March 1931				31 159 675

Incidentally the statistics of yarn spun in Ahmedabad during the years 1923 to 1930 are relevant in this connection. They also are given in Table 3.

The static condition of trade in Bombay led to a slackening in the demand for suburban development. The population was naturally reluctant to move out to the suburbs so long as accommodation of almost any kind was available close to the working quarters, and the congestion has not so far reached such a pitch as to force any considerable outward movement. While it is always dangerous to prophesy, it seems certain that more settled conditions in India generally, the recovery of

trade, the natural growth of the population, and the possibility of development in only one direction, will, in due course, result in a more rapid growth of the traffic on the Bombay suburban lines, which will be greatly facilitated by this electrification scheme.

Thus it is easy for Poona residents to spend the day in Bombay without an uncomfortably early start or late return.

TABLE 3.

Statistics of Trade in Bombay and Ahmedabad.

	1923–24	1924–25	1925–26	1926–27	1927–28	1928–29	1929–30
Value of trade of Bombay Port, rupees × 10^7	—	—	304	245	251	257	237
Yarn spun in Bombay Island, lb. × 10^6	270	327	262	345	319	154	263
Yarn spun in Ahmedabad, lb. × 10^6	76	92	103	106	111	117	136

Reasons for Electrifying the Main-Line Sections.

The reasons for electrifying the main lines to Igatpuri and Poona were quite different. A substantial additional revenue was hoped for from the improvement in the passenger service between Bombay and Poona, though no account was taken of this in the financial estimates of the scheme. Poona, which is 119 miles by rail from Bombay, is not only an important town in the military organization of India, being the headquarters of the Southern Command, but is also the headquarters of the Government of the Bombay Presidency during the spring and autumn. There is, therefore, a very considerable passenger traffic between Bombay and Poona at all times of the year, and in addition there are a number of race specials during the Bombay racing season between the middle of January and the middle of March, and during the Poona racing season between the end of July and the beginning of October.

Before the completion of the railway up the Ghat, transport between Bombay and Poona was carried on mainly by carriages and carts, the journey taking about 24 hours. In 1863 the railway lines were taken up over the Ghat, the Ghat section being 16 miles long and including one reversing station. On completion of this section, the time to reach Poona was reduced to 6 hours, and more recently to 3¾ hours for mail trains. In 1925, about the same time as the electrification scheme was sanctioned, approval was given to the construction of a new alignment eliminating the reversing station. This new alignment is 2·11 miles in length, and includes three tunnels aggregating 4 598 ft. in length with a section 34 ft. 6 in. wide by 24 ft. 6 in. high, which is believed to be the largest tunnel section in the world.

As a result mainly of electrification, and partly of the elimination of the Ghat reversing station, the time from Bombay to Poona has been reduced to 2¾ hours, which includes stops at the bottom and top of the Ghat section to attach and detach a banking locomotive. This is the timing of a new train named the "Deccan Queen," which has been running once daily in each direction since the 1st June, 1930. This train leaves Poona every day at 7.40 a.m. and arrives in Bombay at 10.25 a.m., returning at 5.15 p.m. and reaching Poona at 8.0 p.m.

This improvement in the timing and the service generally, together with the elimination of the steam locomotive, especially on the Ghat section on which there are altogether 27 tunnels, may reasonably be expected in due course, that is, when the present severe depression has lightened, to result in an increase in net revenue from passenger traffic. Such an increase, however, could not be calculated on any definite basis, and had to be regarded as one of the beneficial by-products of electrification. The formal justification rested on the calculated reduction in the cost of working the passenger and goods traffic on the sections included in the scheme.

Mention has already been made of the two Ghat sections, and a few figures as to the cost of steam working on them will show what scope there was for effecting economies by electrification. On the arrival of each passenger train at the station at the top or bottom of either Ghat section, the locomotive was detached, and the train was taken over the section by two special Ghat engines, one in front and one in the rear, if ascending, or both in front if descending. The train was then taken on by another engine. The same method was adopted for all goods trains, except that every normal train was first split up into two parts, each part being then worked over the Ghat by two special engines. The working expenses were necessarily high. Thus for passenger trains the locomotive expenses per train-mile on the Bhore Ghat (S.E. line) were 2¾ times what they were on other sections, and on the Thull Ghat (N.E. line) 3 times. For the goods traffic the locomotive expenses per undivided train-mile were 4½ times on the Bhore Ghat, and 4·8 times on the Thull Ghat, what they were on other sections. There was clearly room for improvement in this direction, especially in regard to the goods traffic. Further, not only would the locomotive costs be reduced, but also by eliminating the breaking-up and remaking of trains at the top and bottom stations, there would be a saving estimated at Rs. 9 33 000 (£70 000) per annum.

Forecast of Traffic on Main-Line Sections.

The foundation on which any electrification scheme is worked out consists of the statistics of the traffic on the sections considered. Such statistics must be based on the records of past years, and it is obviously necessary to take into account growth of traffic where such is

expected, either as a result of electrification or as due to external causes such as increase or movement of population or industrial development. The preparation of statistics, including the forecast of growth, is naturally a difficult matter, and can only be undertaken by the officers of the railway, who are continually engaged in studying the past records, the current figures, and the various factors which affect the conditions of the future. How far ahead to look is a debatable question. If there is any reason to anticipate a growth of traffic, the actual statistics of the traffic at the time when the estimates are being prepared cannot be taken as a satisfactory basis, either for designing the installation or for calculating the financial results. Equally unsuitable would be the forecast of traffic for the date when the scheme is completed and electric operation starts. It is conceivable that a scheme might not be financially justifiable on this basis or might show only a moderate return, but would be fully justified when dealing with greater traffic a few years later. On these grounds the Railway Board adopted the principle that any scheme put before them should be judged by the estimated results based on a traffic forecast for the fifth year of electric working, assuming, of course, that they considered such a forecast to be reasonable.

For the G.I.P. Railway scheme the forecast of traffic was based on the actual statistics for the years up to and including 1922–23, the latest figures available when the estimates were being prepared. It was assumed that the fifth year of electric working would be the year 1932–33, on the supposition that sanction to proceed would be given shortly after the presentation of the report in 1924, and that construction would be completed during the year 1927–28. Actually, as already stated, the indents for electrification plant and material were not received in London until the end of 1925 and the beginning of 1926, and the scheme was not in full operation until November 1930; thus, taking the first year of electric working as 1930–31, the fifth year will be 1934–35.

Dividing up the total route to be electrified into three sections, viz. Bombay to Kalyan where the suburban traffic terminates and the line forks north-east and south-east, Kalyan to Igatpuri, and Kalyan to Poona, the anticipated volume of passenger, goods, and ballasting train traffic for the year 1932–33 was as shown in Table 4.

From the figures in Table 4 it will be seen that the traffic for which the scheme had to be designed was fairly dense, especially on the Bombay–Kalyan section. Thus, assuming that all the main-line traffic on this section was carried on two tracks (which is not strictly correct, as the two suburban tracks are occasionally used for main-line trains), the total annual ton-miles (hauled) per mile of single-track running line were, according to the forecast, 10 300 000. On the other two sections the traffic was lighter, but still fairly dense, viz. Kalyan–Igatpuri 6 860 000 and Kalyan–Poona 3 960 000 annual ton-miles per mile of single-track running line.

Traffic on Main-Line Sections since Electrification.

The actual figures for the year 1934–35 will, of course, not be available until the latter part of the year 1935, but some idea of the position can be given by quoting the returns for the short period since full electrical operation started. So far as the passenger traffic is concerned, the correspondence with the forecast has been affected by the trade depression in consequence of which the services were reduced in the year 1930–31.

TABLE 4.

Forecast of Main-Line Traffic in the Year 1932–33

	Bombay–Kalyan	Kalyan–Igatpuri	Kalyan–Poona	Total
Average number of main-line passenger trains per day	46·74	19·68	27·06	—
Passenger train-miles per annum, including specials	624 000	399 130	930 370	1 953 500
Gross ton-miles per annum of goods trains (excluding locomotives)	423 380 000	546 130 000	346 540 000	1 316 050 000
Ton-miles per annum for ballasting trains ..	17 500 000	11 000 000	9 220 000	37 720 000

Thus for the five months, September 1930 to January 1931, inclusive, the main-line passenger traffic was at the rate of 1 652 000 train-miles per annum, and for the next six months at the rate of 1 555 000 train-miles per annum.

The position in regard to the goods traffic is less favourable. At the time when the forecast was prepared there was every reason to anticipate that the tonnage of goods traffic into and out of Bombay would continue to increase at more or less the same rate as in previous years. Unfortunately this anticipation has not been fulfilled, partly on account of reasons mentioned above, and partly due to the general situation in India, which need not be discussed here. For the year 1931, which was certainly an exceptionally bad year for the railway, the goods ton mileage was about 567 000 000. The industrial position at present is uncertain, and it is impossible to make a reliable estimate of the goods traffic in the year 1934–35, but while it is improbable that it will reach the figures in the forecast, it can hardly fail to be nearer than it is at present.

GENERAL TECHNICAL CONSIDERATIONS.

Turning now to the technical aspect of this electrification scheme, there are various ways in which the design



FIG. 3.—Plan of transmission lines between Karjat and Lonavla.

Plate 2.

FIG. 4.—Electric train on the Bhore Ghat.

and working-out show differences of detail when compared with other schemes of similar nature and magnitude. These differences had their origin in the circumstances of inception, and particularly in the local physical conditions.

As already related, the complete scheme grew out of the comparatively small beginning, viz. the electrification of the harbour branch for suburban traffic; the application for sanction to proceed with the main-line scheme was not made until after the start of operation on this section. Initially, therefore, the suburban electrification was all-important, and the choice of electrical system was based mainly on this condition, with due regard to the possibility of future electrification beyond the suburban area. It was decided to adopt the 1 500-volt d.c. system, and there has since been no reason to regret that decision. Later, when the designs for the main-line scheme were under consideration, it was decided to continue with the same system, although it would have been possible to raise the voltage on the sections beyond the suburban area to 3 000 volts. If electric working on the Ghat sections had been the only consideration, there might have been, and under present conditions there probably would be, some advantage in adopting the higher voltage, as the power demand per train on these sections is near the limit of practical operation at 1 500 volts. As, however, there was no actual necessity to work at a higher voltage, the advantage of using the lower pressure on other sections, and the simplification arising from a uniform system throughout the complete electrification scheme, provided ample justification for deciding on 1 500 volts for the main lines.

This leads to a general remark on the importance in this electrification scheme of reliability of operation. So far as the suburban services are concerned, it must be admitted that an occasional delay is not such a serious matter to the majority of Indian passengers as it would be to daily travellers in this country, though this, of course, does not imply that the railway is satisfied with any performance below the best obtainable. In regard to the main-line traffic, on the other hand, it must be remembered that Bombay is the gateway of the East, from which overseas mails and passengers, official and unofficial, are carried to all parts of India. A train failure on the electrified sections is comparable in importance with a failure on the Euston–Rugby section of the London, Midland and Scottish Railway, or the King's Cross–Grantham section of the London and North Eastern Railway. Reliability of operation is therefore the first consideration, and this accounts for certain special features in the design of the system and of the locomotives in particular, to which reference is made below.

In a general way the local conditions are fairly well known. Bombay is in the tropics, the average temperature is fairly high, and the humidity very high all the year, and during the monsoon period from the middle of June to the middle of September the rainfall is very heavy. Conditions change, however, as one leaves Bombay and its immediate neighbourhood; the maximum temperature is higher and the minimum lower, and apart from the monsoon season the humidity is much lower. As one approaches the Ghats the rainfall in the monsoon increases, and in the dry season the temperature variation is greater, with a minimum of 40° F. and a maximum sun temperature of 130° F. From the top of the Bhore Ghat to Poona the monsoon becomes gradually less important, and at Poona the rainfall is not much greater than in this country.

In other respects the local conditions are special and peculiar, arising from floods, birds, and insects. Bombay is a low-lying island and, under certain conditions of wind and tide, flood-water from heavy rainstorms cannot drain away. Certain parts of the railway, especially about one to two miles from the terminus, are liable to floods, which on occasion rise to a level 2 ft. 6 in. above the top of the rails. To meet this condition, special provision was made in the design of the motors, and the equipment of some of the suburban trains to enable them to run through the floods without damage.

Birds in many countries are a source of danger to overhead transmission lines. In and around Bombay the flying fox has sufficient spread of wing, with each wing-tip shaped in the form of a hook, to cause occasional short-circuits on 20 000-volt lines. Accumulations of bird droppings on the sheds of suspension insulators give rise to flash-overs from time to time on the 100 000-volt lines. A much more prolific source of trouble in the early days of electric operation was the propensity of crows in and near Bombay to build nests of iron wire, and their special predilection for the braced corners of the overhead-line structures as convenient positions for the nests. It is related that one such nest was built of metal spectacle frames which had been purloined by a crow from an open shop-window. For the making of these nests during the nesting season, the crows fly about with lengths of wire in their beaks, sometimes 3 or 4 ft. long. Such pieces of wire in the neighbourhood of live overhead lines are obviously very objectionable. It was hoped that the crows after one or two seasons would become sufficiently educated to keep clear of live lines when carrying wire, but this hope has not been realized. Special features introduced into the design of the track equipment have successfully dealt with this trouble.

Insects and vermin seem to be strongly attracted to the live parts in the substations, and it is not easy to keep them out. Lizards, which may grow later to a length of 7 or 8 inches, can pass through a crack not much more than $\frac{1}{8}$ in. wide. Mice and rats have been found in the 1 500-volt busbar chambers. In one case three dead rats and one live one were found, but fortunately did not cause a short-circuit. In another substation a large jam-jar nearly full of scorpions was the bag at the end of three weeks' cleaning. As a favourable local condition, mention should be made of the fact that lightning storms are infrequent and, in general, not particularly severe.

Technical Particulars.

Full technical particulars of the complete installation are given for reference in the Appendix, together with the names of the contractors. The following comments may serve to explain certain points which might not otherwise be clear.

Multiple-Unit Suburban Trains.

In 1922 the Railway Board were developing new standard loading and structure gauges better suited to a railway with 5 ft. 6 in. track gauge than those then in force, which corresponded fairly closely to the standards still used in this country. For the electric working of the harbour branch new stock was required, and it was decided that the designs should conform to the new standards. All coaches were, therefore, 12 ft. wide, 13 ft. 9 in. high, and 68 ft. long over headstocks. Each train unit consists of one motor-coach and three trailers, the normal train used during the rush hours being made up of two units. The seating capacity of each unit is 15 first class, 42 second class, and 384 third class, total 441. It is, however, possible to carry more than this; thus, although the seating capacity of a third-class coach is 120, the crush loading is 200. The weight of a 4-coach unit with all seats occupied is about 218 tons. For subsequent instalments of the suburban scheme, existing coaches were adapted for use as trailers, and new 10 ft. wide motor-coaches were purchased. For this stock the seating capacity of a 4-coach unit is 361, and the total weight with all seats occupied is 188 tons.

Each motor-coach is equipped with four 275-h.p. motors; the horse-power per ton of train (12-ft. stock), viz. 5·05, is therefore low compared with other suburban equipments; still lower is the ratio of horse-power to seating accommodation, viz. 2·5 h.p. per seat. As determined by the first of these ratios, the starting acceleration, viz. 0·9 mile per hour per second, is also low. The justification for this figure is that the first cost of the electrical equipment is kept down to the minimum, while the increase in the schedule speed on that of the steam trains working on the existing suburban lines, viz. 25 per cent, is sufficient under the circumstances.

To meet the flood conditions mentioned above provision was made, first, to accommodate the whole of the control apparatus and auxiliary equipment inside the coach, and, second, to enable the motors to be closed completely when necessary, while normally permitting air to be drawn in at the commutator end and expelled at the pinion end by the fan on the armature. For this purpose the usual openings at the commutator and pinion ends were fitted with large rotary valves, which could be closed immediately by merely turning the valve handles.

During these abnormal flood conditions the service is necessarily curtailed, as it is impossible to run at high speed through the flooded area. The last 15 motor-coaches ordered were therefore designed on more usual lines, i.e. provision was not made to enable them to run through water without damage. Thus, although the control equipment was contained in the high-tension chamber inside the coach, the main resistances and the motor exhauster were carried below the underframe, and the motors were built without valves on the ventilation openings.

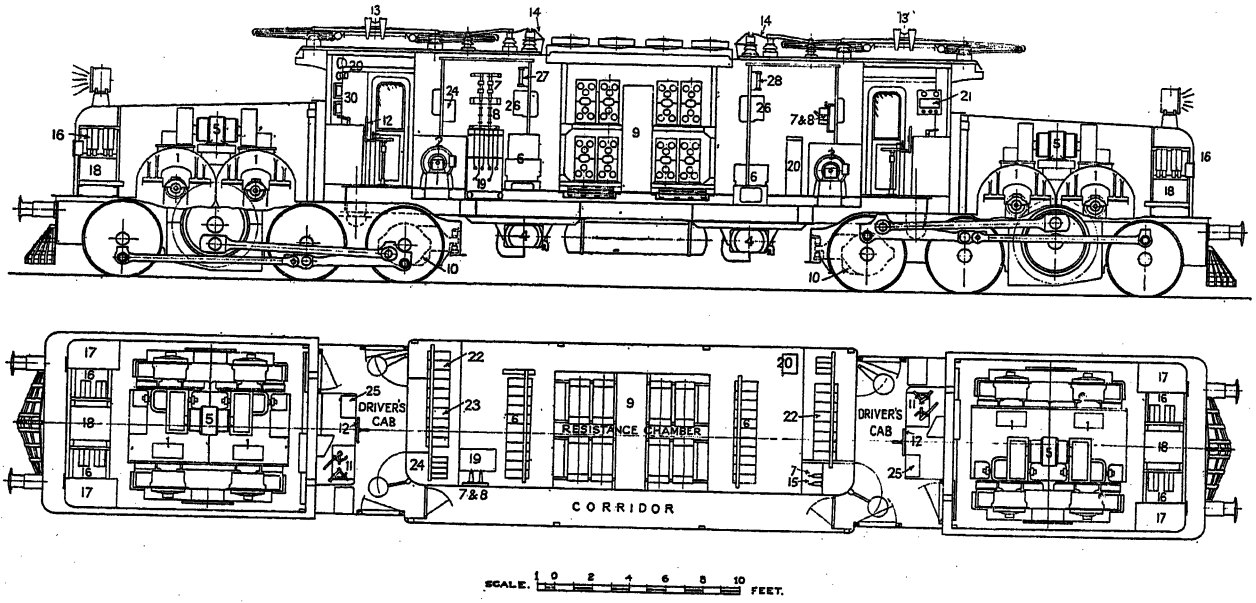


FIG. 5.—General arrangement of freight locomotive.

1. Traction motors.
2. Exhauster and generator set.
3. Exhauster.
4. Air compressors.
5. Motor and blowers.
6. Cam-operated switch groups.
7. Main isolating switch.
8. Auxiliary isolating switch.
9. Main resistances.
10. Axle generator.
11. Master controller.
12. Hand-brake wheel.
13. Pantograph current collectors.
14. Lightning arrestors.
15. Pantograph isolating switch.
16. Weak-field switches.
17. Field resistances.
18. Reverser cam group.
19. 4-way h.t. fuse group.
20. 2-way h.t. fuse group.
21. Lighting switches and fuses.
22. Motor switches.
23. Relays.
24. H.T. auxiliary contactors.
25. Exhauster control cut-out.
26. Resistance switches.
27. Relay resistance.
28. Exciter resistance.
29. Voltmeter and indicators.
30. Ammeters.

*Freight Locomotives.**

As will be seen from the schedule of particulars in the Appendix, and the general arrangement drawing in

* A general description of these locomotives has already been published in the technical Press (see *Engineering*, 1928, vol. 126, p. 163). Reference may also be made to a paper presented to the Institution of Mechanical Engineers by Mr. Twinberrow, entitled "The Mechanism of Electric Locomotives" (See *Proceedings of the Institution of Mechanical Engineers*, 1932, vol. 122, p. 51).

Fig. 5, the design is in accordance with the designation C — C, that is, the wheel arrangement comprises two

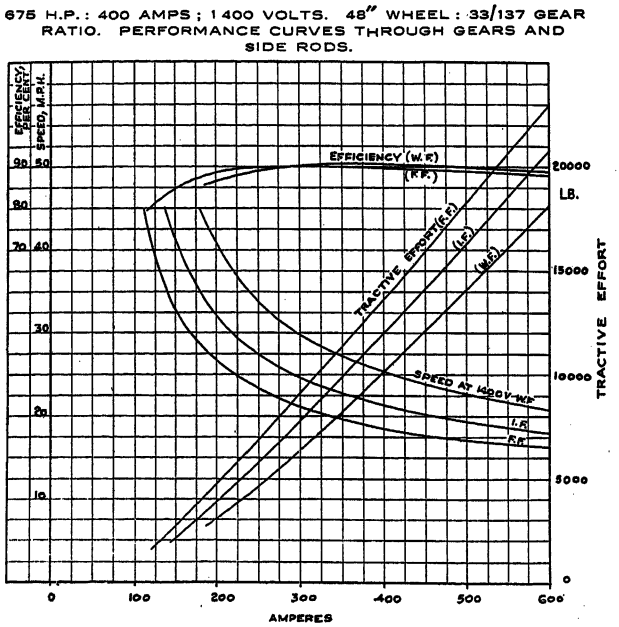


FIG. 6A.—Performance curves of freight locomotive motors (motoring).

F.F. = Full field. I.F. = Intermediate field. W.F. = Weak field.

sets of 3 coupled axles. In view of past discussions as to the use of coupled axles in electric locomotives, it may be of interest to state the reasons for selecting this design in preference to that indicated by the designation $C_0 + C_0$ or, alternatively, $B_0 + B_0 + B_0$, i.e. two 3-axle bogies or three 2-axle bogies, in either case with each axle driven independently by its own motor.

The advantages of the design with coupled axles, as applied to the conditions under which the locomotives work, are as follows:—

(1) There is less tendency to skidding of the wheels than with individually driven axles. Statements have recently been made that there is no difference in this respect between locomotives with coupled and those with uncoupled driving axles, but the anticipation that better results would be obtained with coupled axles has been fully confirmed by comparing the adhesion characteristics of these and the passenger locomotives, to which reference is made below. With the duty required from the freight locomotives it was very important to avoid slipping as much as possible. Trains of 1 240 tons (including locomotives) have to be taken up the 1-in-37 gradients on the Ghat sections, and are liable to be stopped at any point by flag; any delay in getting started again due to slippery rails would be troublesome. Slipping of the rear locomotive alone would probably break the couplings in the middle of the train. Still more important is the condition when two locomotives are taking a load of 1 840 tons down the 1-in-37 gradients with regenerative braking. Any serious slipping of the wheels might then lead to a runaway.

(2) The whole motor equipment is carried on the trucks and is therefore spring-borne. Thus the dead weight per axle is kept down to the lowest possible figure.

(3) The main motors are well above the driving axles,

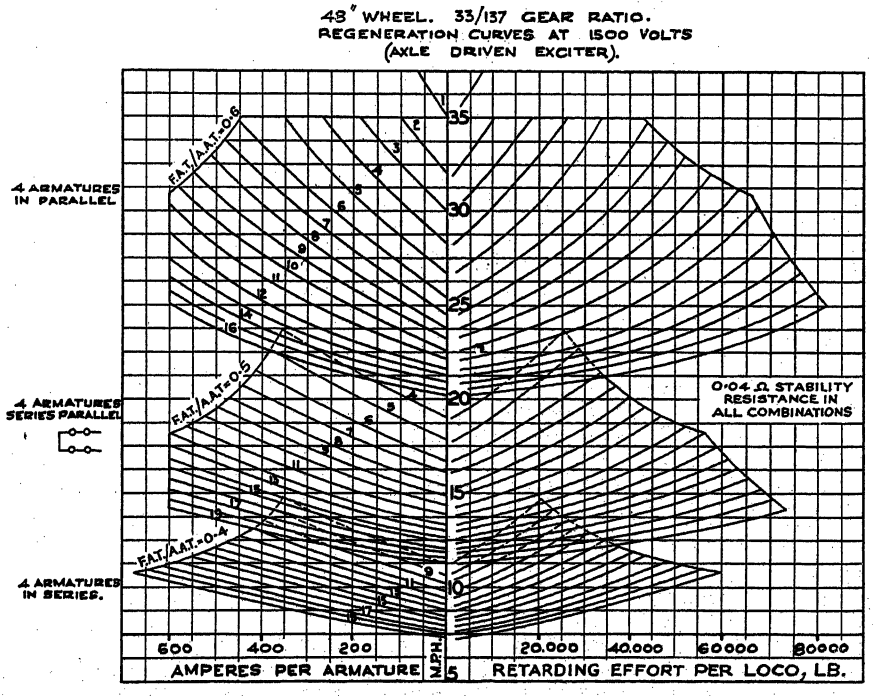


FIG. 6B.—Performance curves of freight locomotive motors (regenerating).

F.A.T. = Field ampere-turns. A.A.T. = Armature ampere-turns.

and the centre of gravity is correspondingly high. This is a good feature in regard to the wear and tear of the track, and to freedom from trouble on account of floods.

(4) The complete electrical equipment is easily and conveniently divided into two groups, so that in the event of any electrical failure one group can be immediately isolated without affecting the operation of the other. This reduces any probability of a train being stalled and blocking the road.

(5) A lower crawling speed is possible with four 1 500-volt motors in series than with six 750-volt motors. Performance curves of the main motors while motoring and regenerating are given in Figs. 6A and 6B.

Before the final decision was made in favour of this design, inquiries were made as to the experience with similar locomotives on the Swiss Federal Railways. The information received showed that there was no reason to regard the coupling rods as an objectionable element of the design, and that in fact the cost of maintenance of the mechanical parts was less than the cost of electrical maintenance.

In order to reduce as far as possible the chance of stalling on the road, certain special features were incorporated in the design. As already mentioned, the electrical equipment was divided into two groups. Two vacuum pumps were provided, one driven by its own motor, and the other by the auxiliary motor-generator; two axle-driven generators for regenerative working were provided, and two motor-driven compressors for brake operation and for the contactor switch groups, pantographs and whistles; the auxiliary 50-volt battery has sufficient capacity to give a supply for lights and control circuits for 4 hours; and an insulated false roof was inserted between each pantograph and the locomotive roof to guard against the possibility of short-circuits due to wires carried by birds.

It might be expected that the two 3-axle trucks would be articulated or close-coupled. It was found, however, on working out the detailed design, that such an arrangement would unduly cramp the space available for the electrical equipment, especially with the duplicate auxiliaries. The clearance between the inner driving wheels of the two trucks is actually 20 ft. 9 in. The locomotive body was built to conform to the old standard gauge with a width of 10 ft., as it would have to work through many tunnels which could not be enlarged to the dimensions of the new gauge.

The number of freight locomotives which are used for banking passenger trains on the Ghats, as well as for hauling freight trains was determined by working out the links on the basis of a new time-table prepared by the chief transportation superintendent for the anticipated traffic with revised electric timings. The number so calculated was 33, and to this was added 25 per cent for spares, shed days, and heavy overhaul, making 41 in all. The number of existing steam locomotives allocated to the 1923–24 goods traffic was 57, in addition to 82 Ghat engines which were used for all trains on the Ghat sections. It was further estimated that, to deal with the additional freight traffic anticipated by the year 1932–33, 18 new goods engines would be required as well as 14 new Ghat engines for the additional freight and passenger traffic. Thus the 41 electric locomotives were provided to replace in all 166 steam locomotives.

Passenger Locomotives.

The desire to increase the traffic between Bombay and Poona has already been mentioned, and an essential feature of the revised service was the improvement in the timing between these points. The consulting engineers were asked to state what could be done in this direction with a train stopping only at the foot of the Bhore Ghat to attach a second engine and at the top to detach. They gave a time of 2 hours 32 minutes (without margin, but including allowances for reducing speed to 10 miles per hour at four points on account of track repairs), provided the maximum permissible speed was raised to 70 miles per hour.

At that time the design and performance of electric locomotives suitable for running at 70 miles per hour were not so well known as they are now, and it was felt that it would be safer to build and try out one or two samples before committing the railway to one particular design. Apart from testing the suitability of the design, the running of these samples would provide an opportunity of making certain of the tractive resistance of the trains to be hauled at this speed, and the tractive efficiency of the locomotive.

For the purpose of the preliminary design, it was estimated that the tractive resistance of a 450-ton train (inclusive of locomotive) would be about 14 lb. per ton at 70 m.p.h., and the specification therefore called for a locomotive with a tractive effort of 6 300 lb. at this speed. Three samples were ordered, one each from the General Electric Co., the Metropolitan-Vickers Co., and Brown-Boveri. The first to be delivered was that supplied by the Metropolitan-Vickers Co., and as soon as possible this was employed in a series of experiments to test its running qualities, its suitability to the Indian climatic conditions, the general design and arrangement of the electrical equipment, the tractive effort at 70 m.p.h., and the tractive resistance of the trains. It was found that the tractive effort was rather below the specified value, and that the tractive resistance was rather higher than the estimate, viz. about 15 lb. per ton on the level in calm weather. Under the circumstances it was thought advisable, when revising the specification for the bulk order, to call for a considerable increase in the tractive effort. After careful consideration and discussion with the officers of the railway, it was decided to specify a tractive effort of 7 500 lb. at 70 m.p.h. It was estimated on the basis of the preliminary tests that this would allow a margin of nearly 2 lb. per ton when running on the level, and would therefore enable the train to keep time against a moderate head-wind. It would also make possible a steady speed of about 57 m.p.h. up a 1-in-150 gradient. The performance curves of the motors in the 21 locomotives finally ordered are given in Fig. 7. Another point to which careful attention had to be given in the design of the motors was that each passenger train going up the Bhore Ghat had to be taken up that section by a passenger locomotive and a freight locomotive working in combination. With the very different speed characteristics of the two locomotives special care was necessary

to ensure a proper sharing of the load at the speed desired. It was accordingly decided that of the total tractive effort required, viz. about 40 000 lb., the passenger engine should be responsible for 16 000 lb., leaving 24 000 lb. for the freight engine, both at the speed of about 26 m.p.h. It was found that this condition was not inconsistent with the other desired speed/tractive-effort characteristics. The combination is obtained by the freight locomotive motors working in full parallel with intermediate field, and the passenger locomotive motors in series-parallel with full field. In practice the arrangement has worked quite satisfactorily. Last year a test was made to decide whether a speed of 30 m.p.h.

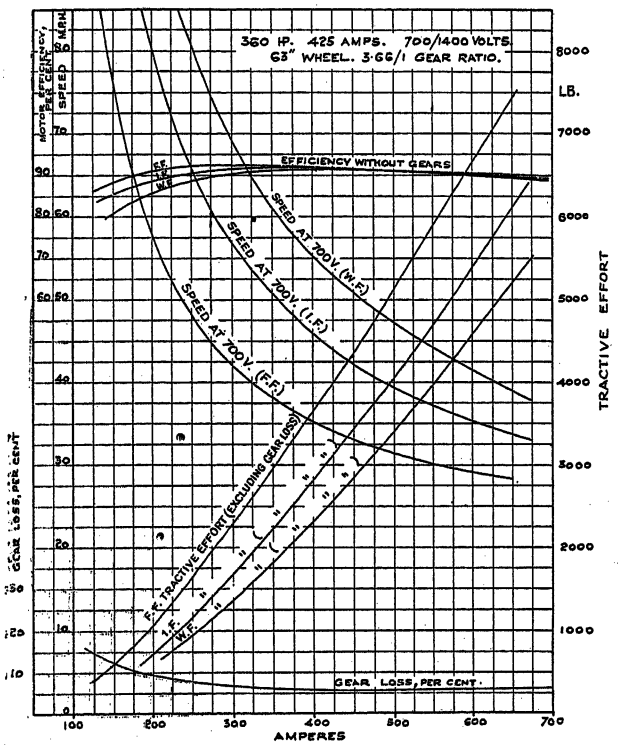


FIG. 7.—Performance curves of Metropolitan-Vickers passenger locomotive motors.

F.F. = Full field. I.F. = Intermediate field. W.F. = Weak field.

was advisable. For this purpose the freight locomotive motors were worked in full parallel with weak field, and those on the passenger locomotive in series-parallel with intermediate field. The result was quite satisfactory, as also was the running of the same train down the Ghat at 30 m.p.h. under regenerative control.

In general the special features incorporated in the design of the freight locomotives to minimize risk of stalling on the road were adopted also for the passenger locomotives. The division of the motor equipment, comprising six 750-volt motors and the main control apparatus, into two groups was not quite so simple as in the freight locomotives where the equipment consisted of two pairs of 1 500-volt motors. The arrangement worked out was, however, quite adequate for the purpose. No provision was made in the passenger locomotives for regenerative braking, as apart from the Ghat sections, on which the freight locomotives take charge of descending passenger trains, the gradients are not sufficient to warrant the extra expense that would be involved. Similarly, the occasions on which passenger trains would be double-headed would be so few that there was no advantage to be gained by equipping the locomotives for multiple-unit control.

Descriptive articles* have from time to time appeared in the technical Press on the three sample locomotives, and there is, therefore, no need to include in this paper an elaborate account of the various details of the designs. It will be sufficient to refer to the schedule of particulars in the Appendix, and to direct attention to the general arrangement drawings in Figs. 8, 9, and 10.

All three locomotives were set to work on the suburban lines, and in December 1928 the order for the 21 additional locomotives to make up the total of 24 was settled in favour of the Metropolitan-Vickers Co. This decision was taken on the following grounds. The General Electric locomotive, although ordered before the other two, was not put on the track for preliminary trials until the beginning of November 1928; the Metropolitan-Vickers locomotive, next in the succession of ordering, started its trial runs in May 1928, and had been on the track for about 6 months with short intervals only in the shops for general maintenance and for a slight alteration at the request of the consulting engineers for experimental purposes. During that period of six months, which included a rainy season, the locomotive had given very satisfactory service, and had exhibited excellent riding qualities at all speeds up to 80 m.p.h., whether attached to a train or running light. The Brown-Boveri locomotive, though ordered last, was delivered about the beginning of August 1928, but on its second run had a serious burn-out which kept it out of service until the beginning of November. In view of the importance of settling the final order promptly if delay in the start of electric working was to be avoided, and in view also of the good performance of the Metropolitan-Vickers locomotive during 6 months' running, there was practically no choice but to proceed as stated. The decision did not imply any dissatisfaction with the other two samples; they suffered from the fact that it had not been possible to run them for an adequate period under service conditions. If the decision had been delayed any longer, not only would the option as to price have expired, but the bulk order could not have been completed before the middle of 1931 at the earliest.

In the sample locomotive the weight per driving axle was limited to 20 tons. During the trial working it was found that there was more tendency for the wheels to slip on the rails in bad weather conditions than had been expected. By comparison with the behaviour of the freight locomotives, it was evident that this was accounted for by the absence of any coupling between the drivers. In working out the final design for the bulk order, a slight modification was made which had the effect of transferring 3 tons from the bogies to the driving axles, so that the weight per axle was increased by 5 per cent, i.e. to 21 tons.

* *Engineering*, 1928, vol. 125, p. 297, and vol. 126, p. 134; also 1929, vol. 127, p. 100.

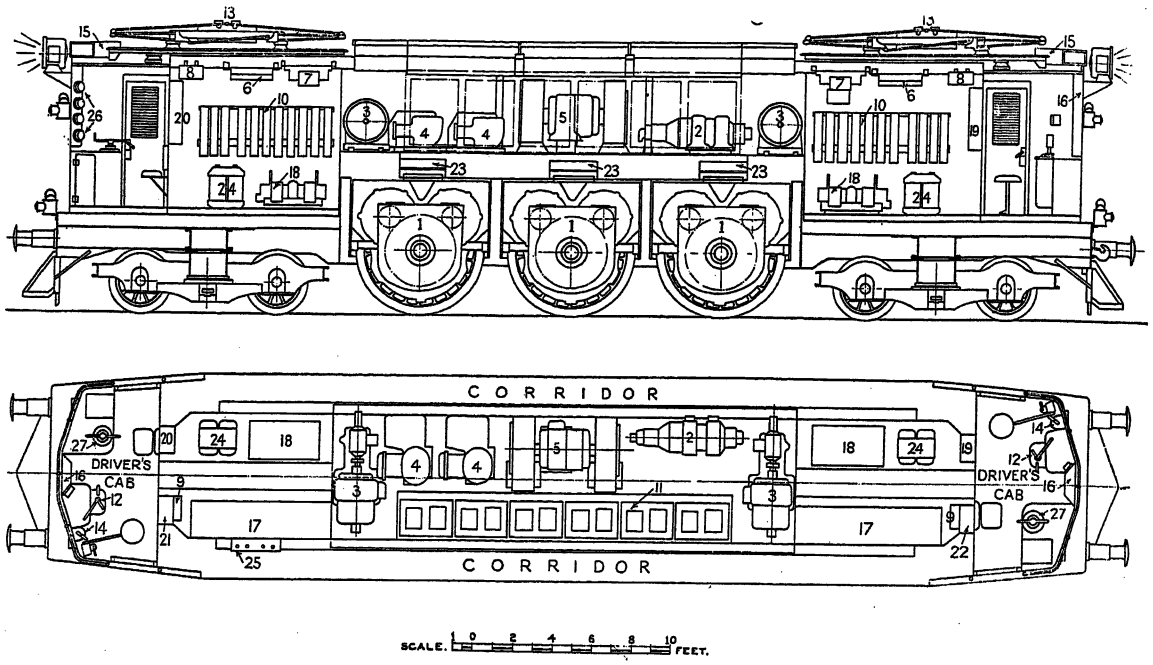


FIG. 8.—General arrangement of General Electric passenger locomotive.

1. Main motors (twin armatures).
2. Motor-generator set.
3. Exhausters.
4. Air compressor.
5. Motor and blowers.
6. Main isolating links.
7. Main choke coil.
8. Auxiliary choke coil.
9. Earth switch.
10. Main contactors.
11. Main resistances.
12. Master controller.
13. Pantograph current collectors.
14. Pantograph switch.
15. Main fuse.
16. Lighting and auxiliary switches.
17. Auxiliary fuses.
18. Reverser.
19. Lighting switches and fuses.
20. Overload relays, etc.
21. No-volt relays, etc.
22. Overload relay and battery gear.
23. Motor connection boxes.
24. Inductive shunt.
25. Cut-out switch.
26. Voltmeters and ammeters.
27. Hand brake.

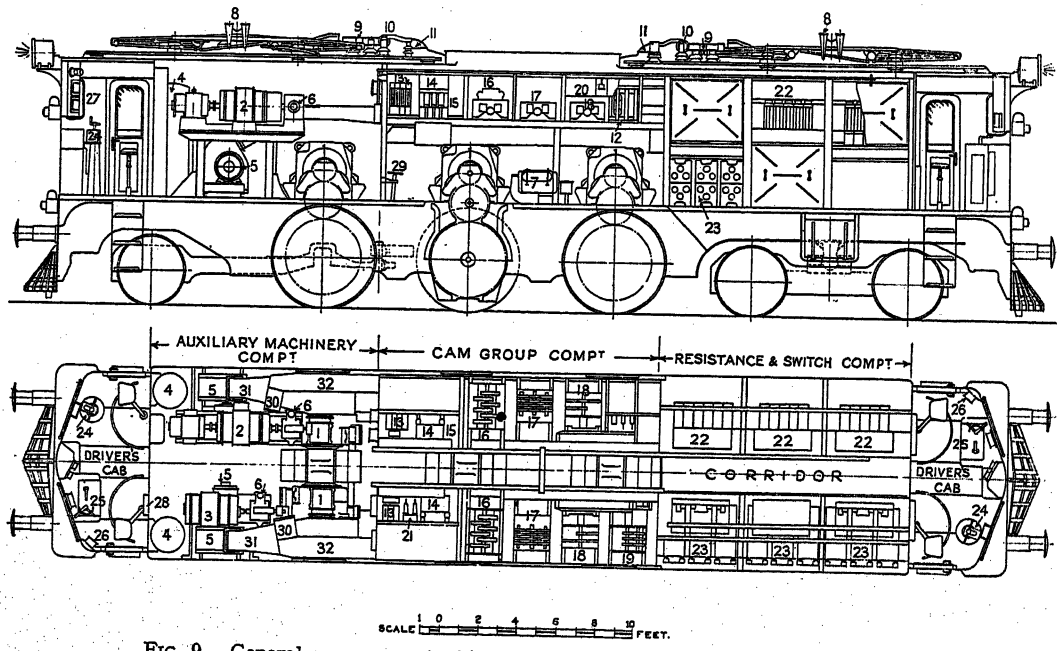


FIG. 9.—General arrangement of Metropolitan-Vickers passenger locomotive.

1. Main motors.
or-generator exhauster set.
uster motor.
ressed-air reservoirs.
s and blowers.
nt collectors.
9. Main equipment fuse.
10. Choke coil.
11. Lightning arrestor.
12. Pantograph isolating switch, etc.
13. H.T. auxiliary contactors.
14. Expulsion-fuse group.
15. Auxiliary isolating switches.
16. Weak-field cam group.
17. Reverser cam group.
18. Motor combination cam group.
19. Motor cut-out cam group.
20. Overload relay.
21. Main isolating switch.
22. Unit switch groups.
23. Resistances.
24. Hand brake.
25. Master controller.
26. Speed indicator.
27. Ammeters.
28. Lighting fuse-box.
29. Hand pump.
30. Motor connection boxes.
31. Air ducts.
32. Cable ducts.

The number of locomotives required was determined by the same method as was employed for the freight locomotives. The 24 electric passenger locomotives displaced 47 existing steam locomotives and rendered unnecessary the purchase of 14 new steam locomotives for the additional traffic anticipated.

Track Equipment.

In general the design of the overhead-line construction followed the precedent set by other electrification schemes carried out by British contractors, especially those in Australia and South Africa. In the first instalments, viz. those on the harbour branch and the suburban were attached to the catenary wire, covering it for about 2 ft. 6 in. each side of the point of suspension.

As will be seen from the particulars in the Appendix, all the running lines within the suburban limits, i.e. all four tracks between the terminus and Kalyan, were equipped with a 0·25-sq. in. contact wire and a 0·375-sq. in. catenary (with the exception of a short experimental length of a different construction). With this section of copper for each of the four tracks, and considering that the line is practically flat, the total conductivity between substations was ample for all requirements.

For the main lines beyond Kalyan, where the 4-track construction terminated and connected with two tracks

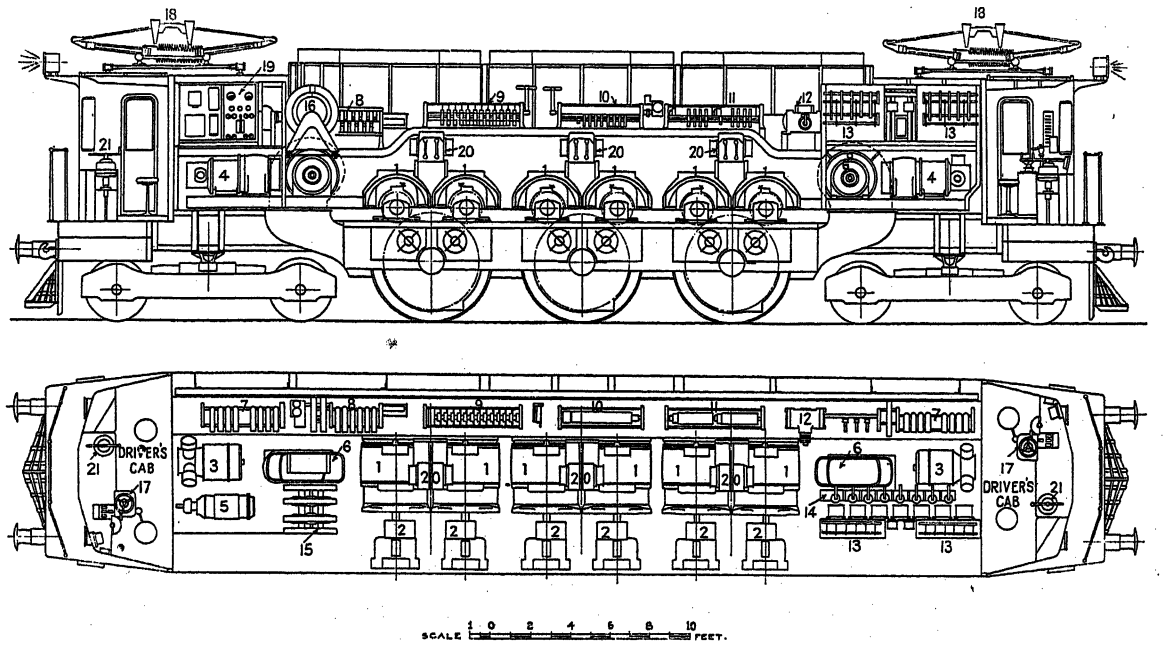


FIG. 10.—General arrangement of Brown-Boveri passenger locomotive.

1. Main motors (twin armatures).
2. Housings for connections to mechanical drive.
3. Air compressor and motor.
4. Exhauster and motor.
5. Motor-generator set.
6. Blower and motor.
7. Cam-operated main controllers.
8. Combination switch.
9. Equipment half cut-out switch.
10. Reverser switch.
11. Cut-out switch.
12. Electro-pneumatic operating apparatus.
13. High-tension fuses.
14. Contactors.
15. Main switch.
16. Automatic circuit breaker.
17. Master controller.
18. Pantograph current collectors.
19. Switch panel.
20. Field control resistances.
21. Hand brake.

tracks of the main line as far as Thana, the catenary insulators were of the well-known diabolo type, carried on the top of the bridge structures, with similar insulators for the steady arms. It soon became clear that this construction offered too much opportunity for short-circuits due to the wire-carrying habits of the crows, and it was necessary to shield the catenary wires and clamps and the live parts on the pull-off insulators by suitably designed insulating plates and fixtures. After trial with one or two different materials, a satisfactory arrangement was reached which for all practical purposes overcame the trouble.

For the final instalment of the suburban scheme and for the whole of the main-line scheme, suspension-type insulators were adopted for supporting the catenary and for side registration of the contact wire. In every case two insulator units giving double insulation were provided between live parts and earth, and bird guards

to the north-east and two to the south-east, on which gradients are more frequent and in many places severe, it was necessary to provide more copper over each running track. It was decided to increase the total sectional area to 1 sq. in. Various methods were available of distributing this total amount between contact and catenary wires and feeders, and before the final decision was made an experimental section about a mile in length between Thana and Kalyan was equipped with a double contact-wire construction with alternately spaced droppers. It was felt that this might have certain advantages, especially in view of the high-speed running that was called for. Experience showed that although the double-contact wire when newly erected or adjusted provided an excellent means of collecting current at high speed without sparking, the superiority over a heavy single-contact wire was not marked. On the other hand, the double-contact line was more difficult to keep in adjust-

ment, and for the same amount of maintenance the single line was equally good, if not rather better. It was therefore decided to adopt a 0·3-sq. in. contact wire with a 0·2-sq. in. auxiliary (or intermediate) and a 0·5-sq. in. catenary, all of hard-drawn high-conductivity copper. the number of insulators and the cost of construction, the new departure was considered as fully justified. Practical experience has shown that expectations have been fulfilled, and that there is every reason to be satisfied with the operation of the line.

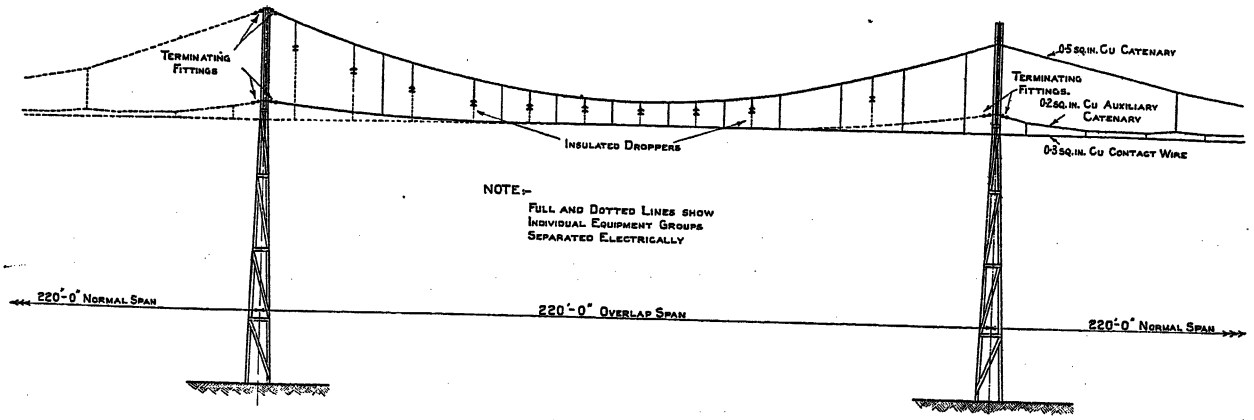


FIG. 11.—Arrangement of main-line track equipment at overlap spans.

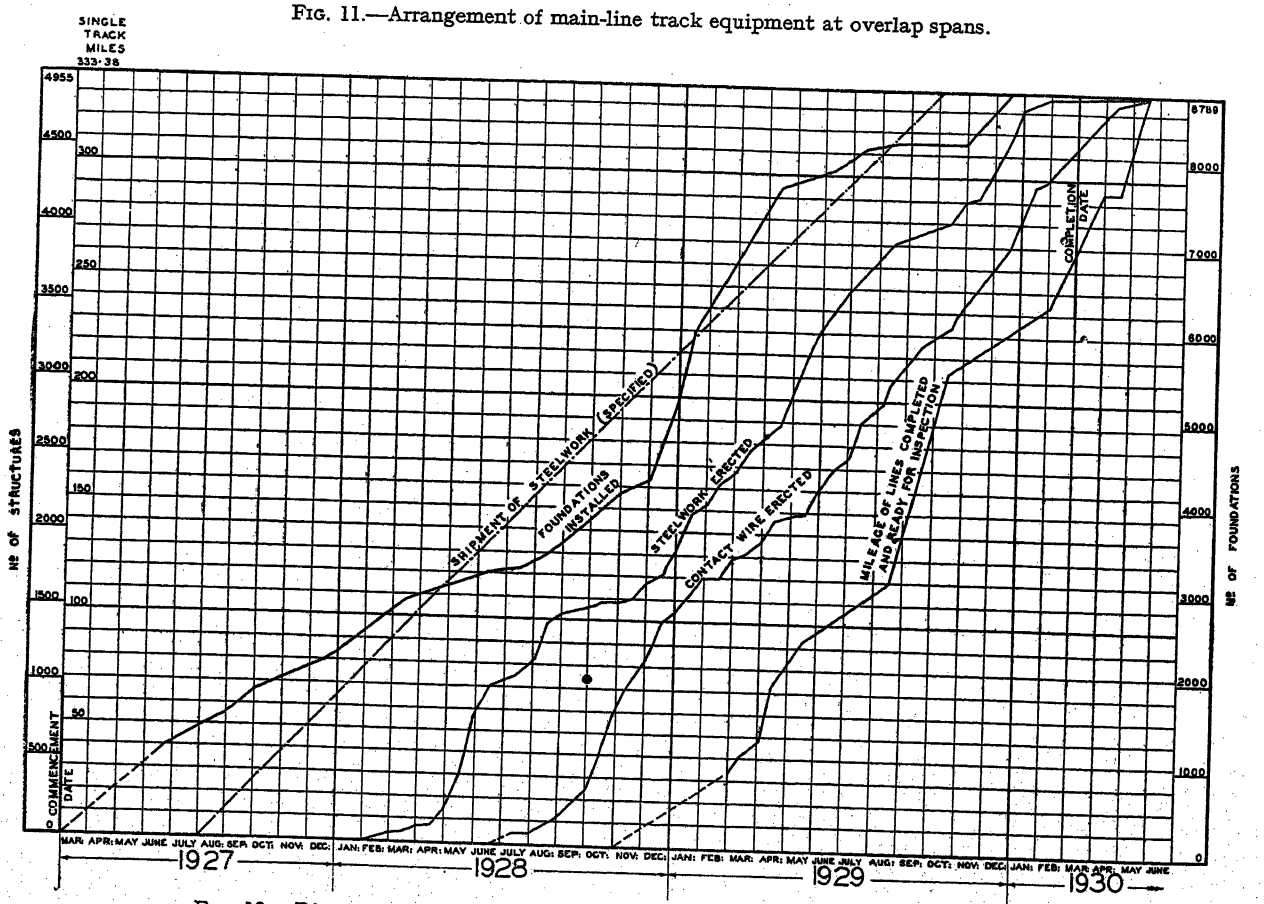


FIG. 12.—Diagram of erection progress of overhead track equipment on main line.

These sizes were an advance on previous installations, e contractors, the British Insulated Cables, Ltd., heir experience that they were enabled all subsidiary feeders to refore reduced to a minimum

A further question to be considered was whether arrangements should be made for automatic adjustment of the tension in the contact line. Close to Bombay the range of temperature is comparatively small, but further inland, especially above the Ghats, low temperature is

usual during the cold weather season at night, and high temperature during the day immediately before and after the monsoon. The limits stated in the specification were 40° F. and 160° F. In order to avoid unnecessary complication and expense, it was decided that provision should be made in the first place for rigid anchoring, but that, if required, automatic tensioning could be introduced by the addition of tensioning springs, or balance weights and pulleys. So far it has not been found necessary to depart from the original arrangement with rigid anchoring.

Certain parts of the Ghat sections are subject every year to damage due to falls of rock during the monsoon. It was recognized that such falls, while they might or might not cover the track or displace the rails, would almost certainly injure any overhead line structure which might be hit. The probability of a structure being hit is, of course, small, but it was thought advisable to take precautions to prevent both tracks being simultaneously affected longer than was absolutely necessary. For this reason, single-track structures were used for each line on all sections subject to this trouble, and the structures were specially designed so that if they were knocked over they would fall clear of the overhead wires of the other track. Thus repair work would be limited to one line, and as soon as the damaged structure was removed, traffic could be resumed by single-line working on the other line.

Mention may be made of the sectioning of the overhead line by means of overlap spans. On level tangent track the line is tensioned and anchored at intervals of about 1 mile; on gradients steeper than 1 in 100 the tension lengths are reduced to about ½ mile. The arrangement of the overlap span is shown in Fig. 11, the purpose of the design being to reduce to a minimum the unbalanced forces on the overlap structures, and consequently the cost of these structures and their foundations.

All structures are bonded to the rails, either directly or through spark-gaps. On the suburban sections direct bonding is only employed in the vicinity of the substations. On the sections beyond Kalyan, where the lines run mainly through open country, no spark-gaps have yet been installed, but possibly after further experience it may be found advisable to do so in some places.

To guard against corrosion of the foundation bolts of the structures on the main-line sections, which are bolted down on top of the concrete foundation blocks, plates of insulating material are inserted between the structure bases and the bolts. Thus, while the structures are bonded direct to the rails, there is no electrical connection between the rails and the bolts embedded in the concrete. On every ground this is a more satisfactory arrangement than connection through spark-gaps.

On the settlement of the main-line contract in March 1927, completion of the work, comprising the equipment of 272 miles of running tracks and about 66 miles of sidings, was called for in 3 years, i.e. by the 1st March, 1930. Fig. 12 shows the rate of progress of the various portions of the work during the carrying out of the contract.

Bonding.

For tracks other than sidings two bonds are used and placed under special fishplates, and for sidings single bonds are used. Owing to the likelihood of theft the welded type of bond could not be considered. The work of installing the bonds was carried out by the railway staff with practically no interference to traffic. In the suburban area drilling of the rails for the bond plugs was for a time carried out by hand drills, but later petrol-electric sets were provided which, by means of lengths of cable fitted at frequent intervals with connectors, supplied electric drilling and nut-running machines. It was found that 1 300 ft. of cable was sufficient to enable a full day's work to be carried out on two tracks, i.e. a length of 2 600 ft., without moving the generating set.

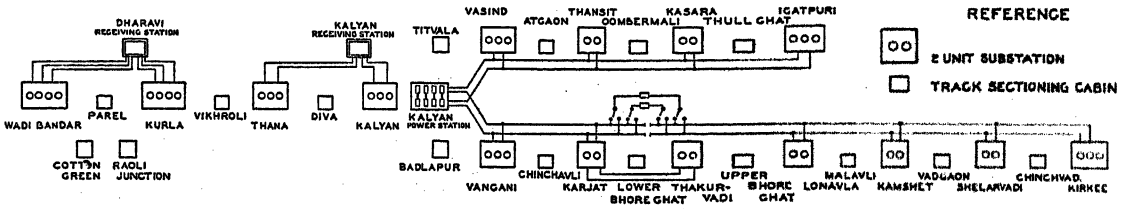


FIG. 13.—Diagram showing distribution of substations and track cabins on suburban and main lines.

Substations.

The general diagram of the distribution of substations and track sectioning cabins is given in Fig. 13. As may be seen in the Appendix, the converting plant in all substations consists of rotary-convertor sets, each set comprising two 750-volt 1 250-kW machines in series to give a 1 500-volt d.c. supply. As mentioned below, power for the initial instalment of the electrification scheme was purchased from the Tata Companies as 3-phase 50-cycle alternating current at 22 000 volts. When subsequently it was decided to proceed with the electrification of the main lines and to build a railway power station for the purpose, the possibility of linking up this station with the Tata system was borne in mind, and the station was designed for the same frequency. All rotary convertors in the main-line substations, therefore, consist of two machines in series. No justification in respect of first cost or operation, sufficient to warrant the installation of single-armature 1 500-volt convertors, was put forward.

In the first 3 substations, viz. those at Wadi Bandar, Kurla, and Thana, the positive side of each set is connected to the 1 500-volt busbar through a low-speed circuit breaker, and the negative to the negative busbar through a limiting resistance short-circuited during operation by a high-speed circuit breaker. The positive

feeder switches are of the same design as the machine circuit breakers, but of smaller capacity. All switchgear, including that for starting, synchronizing, and connection to the busbars, was designed for manual operation, and the circuit breakers are of the switchboard type.

negative circuit breakers were inserted. All the feeder breakers and the positive machine breakers are of the truck type, each truck being inserted into a separate cubicle or cell and connected by a plug-and-socket joint to the busbar which is contained in an enclosed busbar chamber at the back of the cells. For maintenance

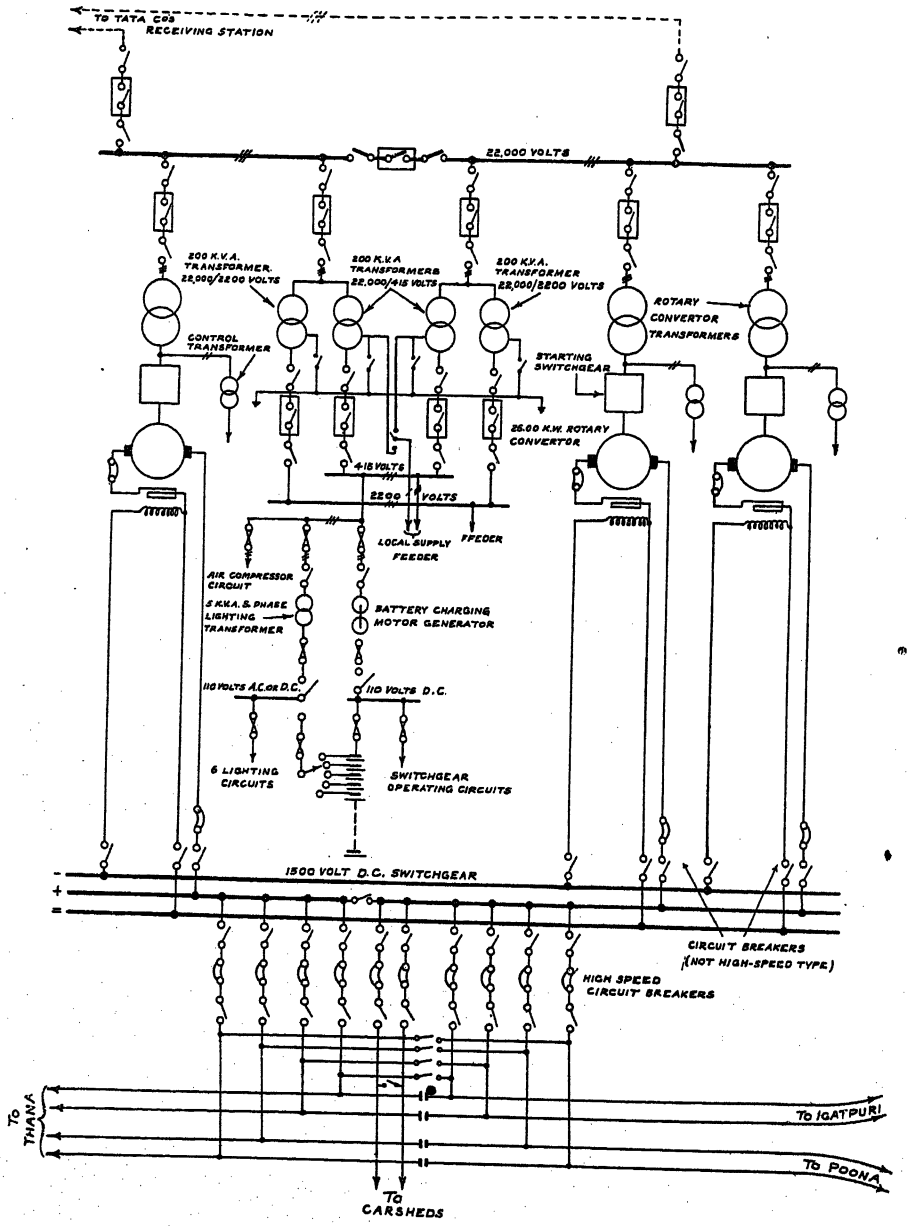


FIG. 14.—Diagram of connections at Kalyan substation.

In the fourth substation, viz. that at Kalyan, from which power is fed in three directions, the general design of the 1 500-volt d.c. switchgear was changed. The protection afforded by high-speed circuit breakers was applied to the feeders, the machines being connected to the positive busbar through low-speed overload breakers. Originally the machine negatives were connected direct to the negative busbar, but subsequently

purposes the trucks are withdrawn, and in order not to leave an open-circuit on the corresponding feeder the circuit breaker is by-passed through a cross connection and a hand-operated switch to the other positive feeder to the same track. This arrangement, which has been applied to all substations and track-sectioning cabins, was not necessary so long as electric working was confined to the suburban passenger services, as the system

was shut down every night for 3 or 4 hours. When the electrical operation of the main-line services started, all lines had to be kept alive continuously, and it was considered desirable that switchgear maintenance should not interfere with the supply of power to any section. A simplified diagram of connections for the Kalyan substation is shown in Fig. 14.

This substation was the first in this scheme in which automatic operation was introduced. Each rotary-convertor set is automatically started, synchronized, and connected to the busbars following the closing of a low-voltage control switch. The substation is in the charge of three shifts of attendants, but all the gear is so arranged that at any time if desired it can be changed over to supervisory control from the power station or power controller's office.

In general, the main-line substations on the north-east and south-east lines are similar to that at Kalyan, the principal differences being (*a*) that all, except one (that at Thakurvadi), take power at about 100 000 volts; (*b*) that 6 of the 11 substations are unattended and fitted for supervisory control from the neighbouring attended substations; and (*c*) that all rotary-convertor sets and their switchgear are designed for receiving power from the 1 500-volt d.c. line from locomotives regenerating, as well as for normal operation. The general arrangement of a typical double-unit substation with outdoor e.h.t. switchgear is shown in plan and sectional elevation in Fig. 15, and a diagram of the main connections in Fig. 16.

As indicated above, only 6 of the main-line substations are on supervisory control. These are situated practically in the open country away from towns; special arrangements for housing substation attendants would otherwise have been necessary. Under the circumstances it was not considered advisable to dispense altogether with attendants and control all the substations from a central point, e.g. Kalyan. With the scheme adopted no controlled apparatus in any substation or switch cabin is more than 24 miles from the controlling point, so that any trouble on the supervisory lines is confined to a few sections of the track. It is perhaps too soon to judge whether the decision to retain a certain number of attendants was unduly conservative.

The circuit breakers in the track sectioning cabins between Bombay and Kalyan are operated by remote control from the nearest railway stations or signal cabins, and in those on the main-line sections beyond Kalyan

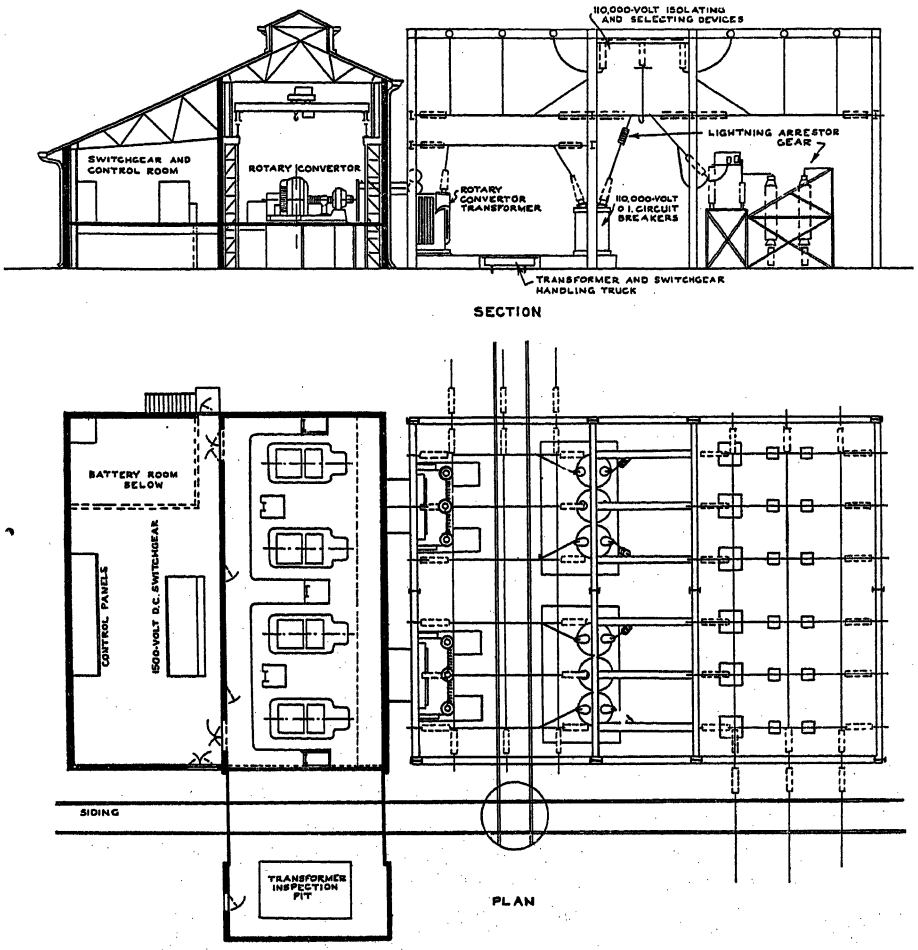


FIG. 15.—General arrangement of double-unit substation with outdoor e.h.t. switchgear.

by supervisory control. For purposes of control, the main switchgear in some of the cabins, viz. those that lie between substations under different control, is divided into two groups, the two circuit breakers for the up and down lines north of the cabin in one group, and those for the up and down lines south of the cabin in the other group. The two groups are controlled from different points, and in this way any section of overhead line can be made alive or completely isolated immediately by a single operator, thus avoiding any delay due to division of responsibility. The general arrangement is shown diagrammatically in Fig. 17.

In all substations the negative busbar is connected to the track rails but not to earth, in order to minimize any liability to trouble from electrolytic action in pipes or other metallic circuits paralleling the track, or from corrosion of track structure foundations. Following on one or two instances of trouble during the early days of operation arising from the breakdown of insulation and the consequent earthing of the 1 500-volt system, in which the short-circuit current through the earth back to the substation was insufficient to open the circuit breakers, a special device was installed in every sub-station and track-sectioning cabin, consisting of a spark-gap in a neon tube, and an electrically operated earthing switch. In the event of the difference of potential between the negative busbar and the earth system in the substation rising to 160 volts or more, as will happen if the 1 500-volt system goes to earth at any point fed

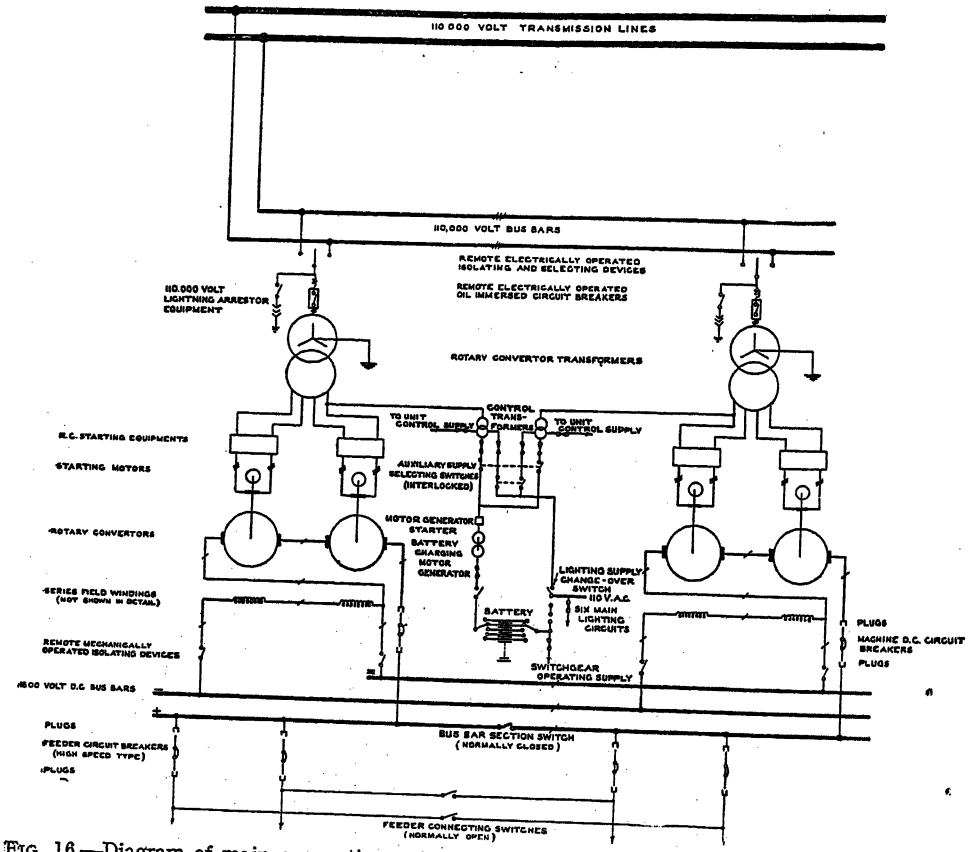


FIG. 16.—Diagram of main connections of double-unit substation with outdoor e.h.t. switchgear.

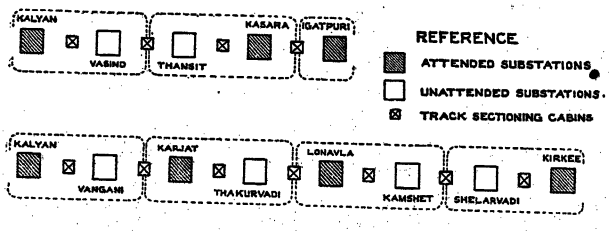


FIG. 17.—Diagram showing groups controlled from attended substations.

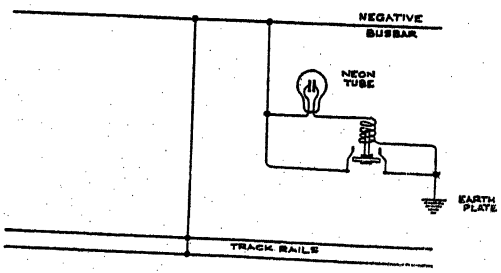


FIG. 18.—Diagram of substation negative busbar earthing device.

from that substation, a discharge passes through the spark-gap and closes the earthing switch. The negative busbar is thus earthed and the fault current becomes a short-circuit current sufficient to open all feeder breakers feeding into the fault. The arrangement is shown diagrammatically in Fig. 18.

A description of the supervisory control equipment of the main-line substations has already been published in the technical Press.* The design of the main equipment will be clear from the particulars given in the Appendix, but mention may be made of the precautions against the entrance of vermin into the 1 500-volt switchgear. The positive busbar chamber is completely enclosed, the connection from the busbar to the circuit-breaker cell passing through a sealing insulator fixed to the partition wall. (In the original design the connection passed through an opening in the wall, and it was through this opening that the rats mentioned above entered the busbar chamber.) The circuit-breaker cell is normally closed in front by the front wall of the truck, and above by a panel of fine-mesh wire gauze high enough to be out of reach of the arcs from the circuit breaker. A plain front is also provided to close the cell when any truck is withdrawn for maintenance of the switchgear.

Transmission System.

All power for the traffic working and for other purposes between Bombay and Kalyan is purchased from the Tata Companies at 22 000 volts. The point of supply for the substations at Wadi Bandar and Kurla is the Tata receiving station at Dharavi, where the 100 000-volt transmission lines from the hydro-electric stations on the Ghats terminate. From this point underground cables are laid to the two substations (for particulars, see Appendix). The other two substations, at Thana and Kalyan, are fed by the Tata Companies' overhead 22 000-volt lines from their Kalyan receiving station.

For both main lines beyond Kalyan power is delivered to the substations by e.h.t. transmission from the Railway power station at Kalyan. One of the Tata Companies' transmission lines delivering power to Bombay passes just outside Kalyan, and the average voltage on these lines at this point is about 95 000. It was decided, therefore, in view of the possibility of future interconnection, to fix the voltage on the outgoing feeders from the power station at 95 000 volts. Two single-circuit transmission lines run along each of the main lines to the furthest substation, viz. Igatpuri on the north-east, and Kirkee on the south-east. For reasons of security, and to avoid interference with telegraph and telephone lines, the transmission lines were erected not less than 300 ft. from the railway line on each side.

The question of power transmission over the Bhore Ghat required careful consideration. With a rise of 2 000 ft. in a short distance, the ground is naturally very rough and uneven, with deep ravines and steep hills. The railway line winds in and out on numerous high banks and through many tunnels. Some idea of the formation may be gathered from Fig. 3 (Plate 1, facing page 916) and from Fig. 4 (Plate 2). Various plans were prepared for running the transmission lines from Karjat at the bottom of the Ghat to Lonavla at the top, with connection to the substation at Thakurvadi about half-way up. It was found very difficult to site the two lines so that access could readily be obtained to them for maintenance and repairs. In view of the importance of this section, as in the event of a failure of both lines all traffic would be stopped between Lonavla and Poona, it was decided to reduce the difficult portion to the shortest possible length by running the two lines along the branch railway from Palasdhari to Khopoli, and to make a special section from this point to Khandala, a distance of only 3 miles as the crow flies, with a rise of about 1 650 ft., and to secure this section by providing a third line which could be put into service immediately in place of either of the other two in the event of a serious breakdown. From Khandala to Lonavla the formation presented no difficulty. The arrangement is shown in plan and profile in Figs. 3 and 19. It will be seen from Fig. 3 that the lines to Khopoli are at some distance from Thakurvadi. The substation at this point is an important one as it is in the centre of the Ghat section of the railway, and supplies power for the ascending trains and absorbs power from the descending trains. As a spur from the Khopoli lines to Thakurvadi would have to cross difficult country, it was thought better to step down to 22 000 volts at Karjat, and run a duplicate supply at this pressure to Thakurvadi, by means of overhead lines on the track structures in the open and armoured cables through the tunnels.

Four outgoing lines leave the power station on two double-circuit towers and divide up close to Kalyan railway station into four single-circuit lines, two going to the north-east and two to the south-east. Each of the two double-circuit lines forks at the dividing point into one to the north-east and one to the south-east. The arrangement at this point is shown diagrammatically in Fig. 20. The south-eastern lines are sectioned at Karjat, where cross-connecting switchgear is installed in the outdoor substation, as shown in Fig. 13.

Power Station.

After studying various alternatives, including several nearer Bombay, a site about a mile south-west of Kalyan was selected. The advantages of this position were: (1) The station could be built close to the railway line and not too far from the river Uhlas from which an ample supply of circulating water could be taken; (2) although practically the whole of the ground between the railway and the river in this neighbourhood is liable to flooding during the monsoon, only a small amount of levelling and filling was necessary to secure close to the railway a sufficient area above flood-level for the power station buildings and extensions, outdoor substation, railway sidings and coal store; (3) there was plenty of high ground on the side of the railway away from the river on which quarters for the power station staff could be built; and (4) the site is close to the point from which feeders run in two directions, to the north-east and the south-east, so that the total length of the transmission system is very little more than the possible minimum.

The plan and elevation of the power station are shown

* *Electrical Communication*, 1931, vol. 9, p. 174.

in Figs. 21 and 22. From these and from the schedule of particulars in the Appendix it will be seen that the main equipment consists of four turbo-alternators each having an economical and continuous maximum rated output of 10 000 kW, and six boilers each designed for an economical output of 60 000 lb. of steam per hour. Each boiler is also designed to maintain continuously an overload output of 75 000 lb. of steam per hour, with an additional 30 000 lb. of steam per hour from fuel oil, making a total overload from coal and oil of 105 000 lb. per hour. A careful study was made of the probable maximum demand on the basis of the anticipated traffic, and it was estimated that the maximum short-period load on the generators (i.e. output plus station

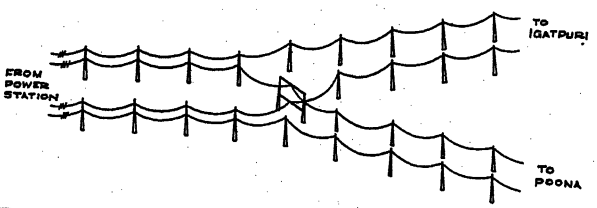


FIG. 20.—Diagram showing bifurcation of transmission lines at Kalyan.

auxiliaries) might be about 31 000 kW. With the generating sets specially designed for high overload capacity, viz. 65 per cent for 2 minutes, two sets should be sufficient to carry the peak load, and more than enough for the average, with one set standing by, and a fourth set for periodical overhaul. At the request of the railway authorities, consideration was given to the possibility of the station being extended in the future to supply power for the suburban as well as the main-line services. The machines were therefore designed to carry an overload of 20 per cent for 2 hours to correspond to the characteristics of the suburban demand.

It was to be expected that the demand for the main-line trains would be fluctuating, with sudden heavy overloads following periods of very light load. Under such circumstances the maintenance of full steam pressure is extremely difficult, and there is a liability for an excessive drop in the speed of the turbines, with a resultant disturbance throughout the system. To guard against this contingency precautions were taken

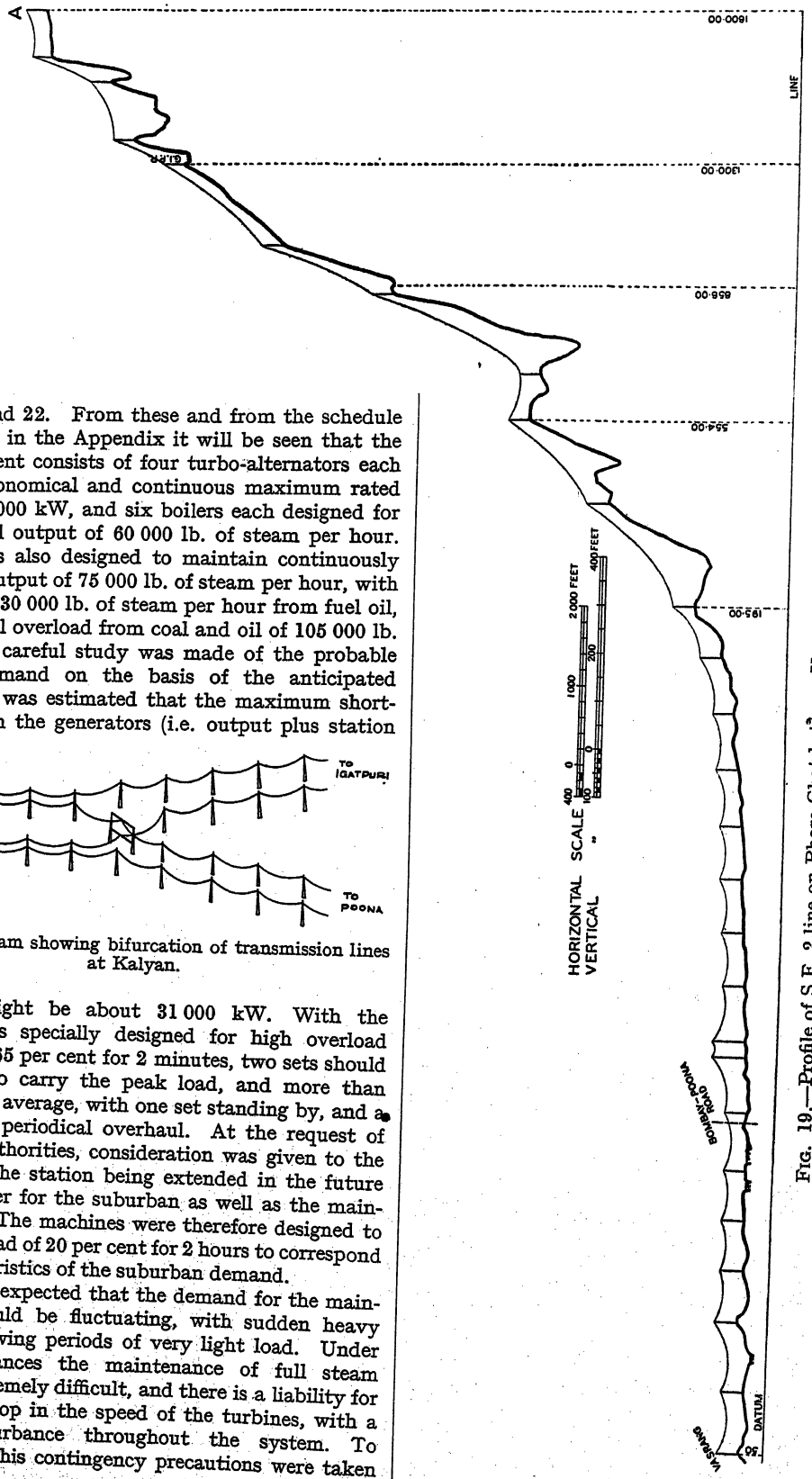


FIG. 19.—Profile of S.E. 2 line on Bhore Ghat between Vasrang and point A (Fig. 3, Plate 1).

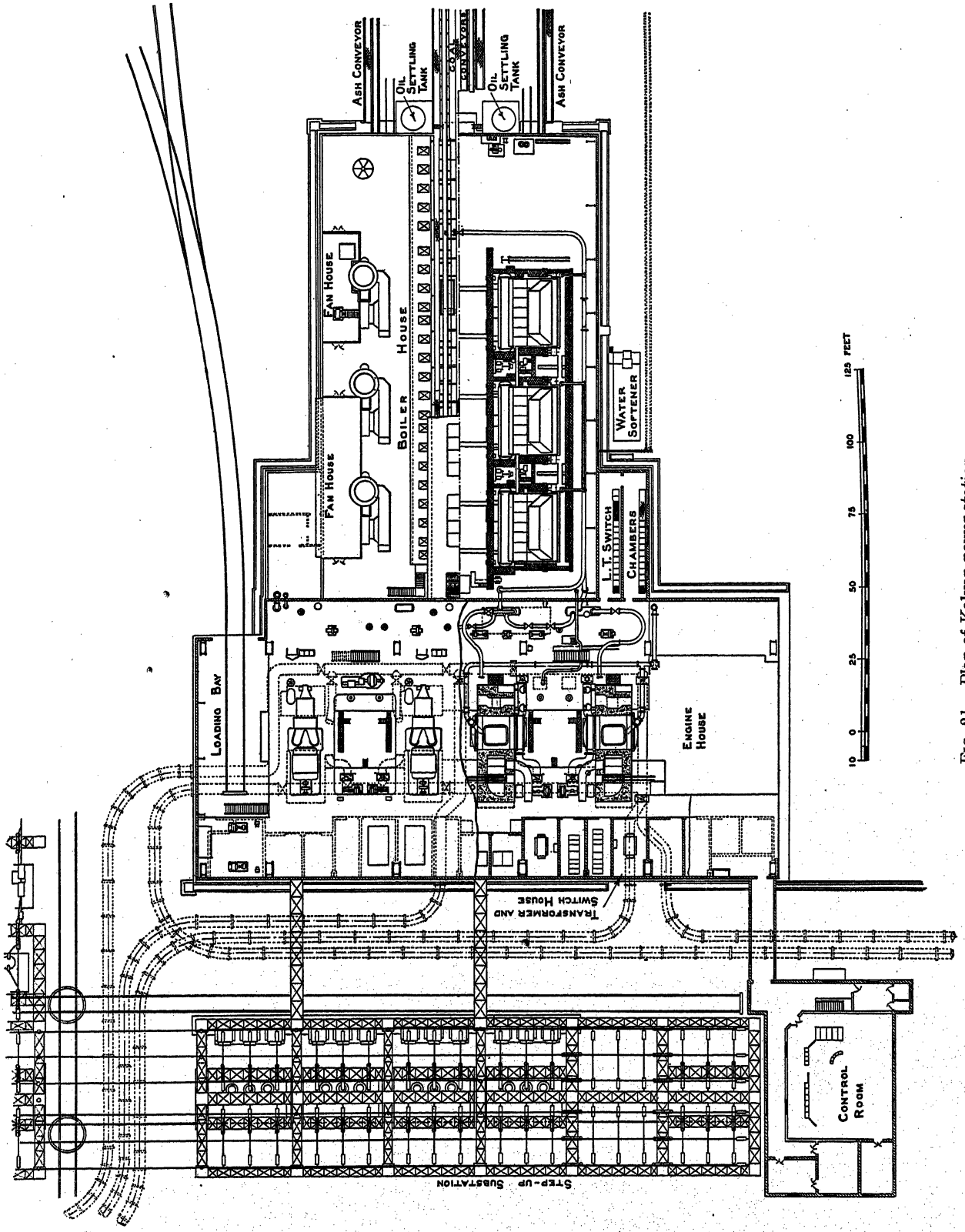


FIG. 21.—Plan of Kalyan power station.

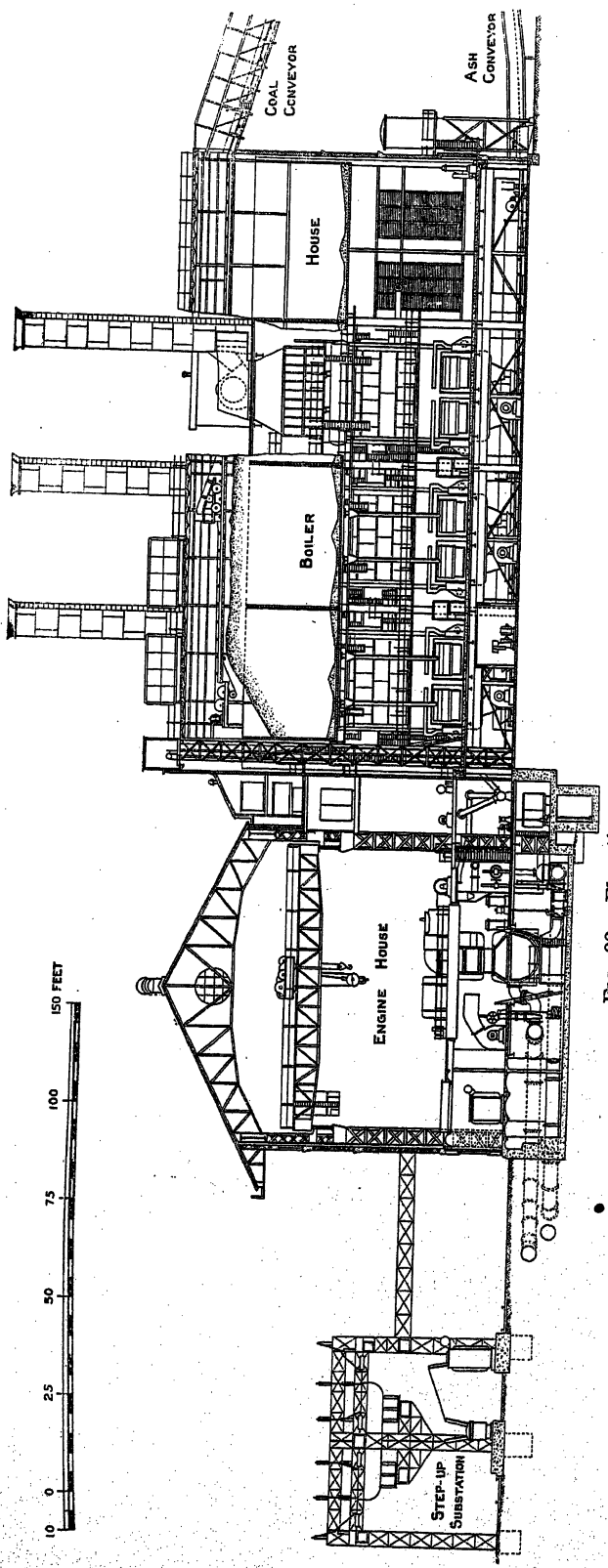


Fig. 22.—Elevation of Kalyan power station.

in two directions. First, the turbines were specially designed so that they could carry the overload of 65 per cent without an excessive drop in speed even if the pressure at the stop valve fell to 190 lb. per sq. in. instead of the normal working pressure of 250 lb. per sq. in. Second, to enable steam to be raised very rapidly, all boilers were fitted with burners for supplementary oil firing, and arrangements were made so that the oil fuel could be turned on at a moment's notice. Thus the boiler-house staff can follow up closely the fluctuations of the load.

As mentioned above, the circulating water for the condensers is taken from the river Uhlas. This is a tidal river, the normal rise and fall of the level being about 6 ft. During the monsoon the river frequently comes down in flood, the maximum recorded height of the flood being 29·3 ft. above the lowest water-level in the dry season. For the intake a screen and pump house was built on the river bank a little up-stream from the power station at a point where there is a well-marked channel in the river near the bank which is not liable to silt up. This pump house was connected with the engine-room basement by three 42-inch diameter cast-iron pipes, each about 960 ft. long. The water, after passing through the condensers, returns to the river through two 42-inch diameter pipes, the outlet being about $\frac{1}{3}$ mile down-stream from the inlet, as between tides the river is stagnant. The temperature of the water in the river varies between 75° and 95° F.

The screen and pump house, the general design of which is shown in Fig. 23, is a massive concrete structure, shaped in the form of a cut-water up and downstream to resist flood pressure and to obviate as far as possible the accumulation of silt in front of the intake openings on account of eddies. Five intakes and five screen chambers are provided, three only being used at present, the total number being sufficient to deal with all the circulating water required for the station when extended by the installation of a fifth turbo-alternator and two additional boilers. The pump suction connections from the back of the screens are so arranged that each pump can draw water from either of two screens. For the present installation only five pumps have been provided, three large ones delivering 16 000 gallons per minute against a head of 47 ft., and two small ones delivering 8 000 gallons per minute against the same head. These pumps deliver into a 42-inch header, from which the three 42-inch pipes lead to the engine-room basement. Above the pump chambers is the pump house which contains the vertical-spindle pump motors, valve hand-wheels, and accessories. At the top of the screen chambers a track is laid for a jib crane, which is thus able to traverse the full length of the inlet frontage and remove any silt that may be deposited in front of the openings.

The principal electrical features of the power station are that all main switching is arranged at 95 000 volts, and that the unit system is employed for the auxiliaries. As will be seen from the diagram of main connections in Fig. 24, each generator is connected through an oil circuit-breaker to the low-tension side of its own 11 000-kVA step-up transformer, and also to the high-tension side of its own 1 800-kVA unit transformer, which feeds the

auxiliaries connected with that set. The 6 600-volt cables from the main alternators lead out from the engine room and connect with solid, circular, copper conductors which are carried across to the framework of the outdoor step-up substation by two overhead lattice-steel girders. As a precaution against short-circuits that might be caused by birds, the conductors are wrapped with maconite tape.

For maintenance purposes a separate building has been erected close to the power station, connected by railway tracks with the engine room and the step-up substation. This building, shown in plan in Fig. 25, contains a transformer and circuit-breaker maintenance shop, electrical repair, machine and fitting, joiners, and blacksmith shops, a store, and switch and transformer handling and conditioning plant.

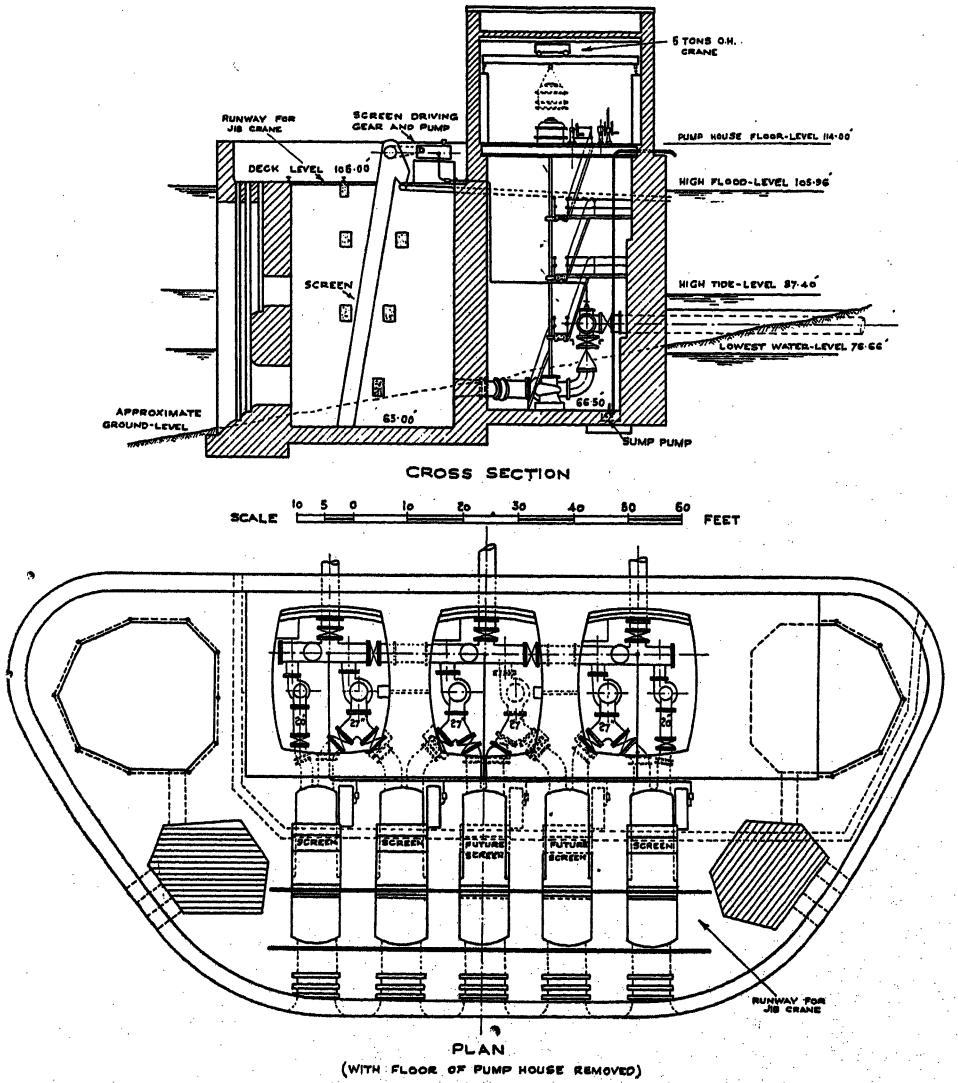


FIG. 23.—General arrangement of screen and pump house.

The control of all main switching is concentrated in the control room. This room is in the upper floor of the control house, a separate building connected with the engine room by a footbridge which also carries the control cables. In the same building are the offices of the power-station superintendent and assistant superintendent, and, on the ground floor, staff offices, mess-rooms, and stores. The operation of the circulating-water pumps is controlled by pilot wires from switch panels in the engine room, and alternatively from similar panels in the pump house.

The boiler house and engine room are steel-framed structures covered with brick and concrete courses. Special attention was given to the question of ventilation in view of the climatic conditions. Instead of the usual louvred clerestory in the roof of the engine room a number of ventilators are fitted along the apex of the roof through which hot air is exhausted. The north wall is provided with hinged glass windows, which can be kept open in nearly all conditions of weather, as the prevailing wind during the rainy season is from the south-west. For the ventilation of the boiler house

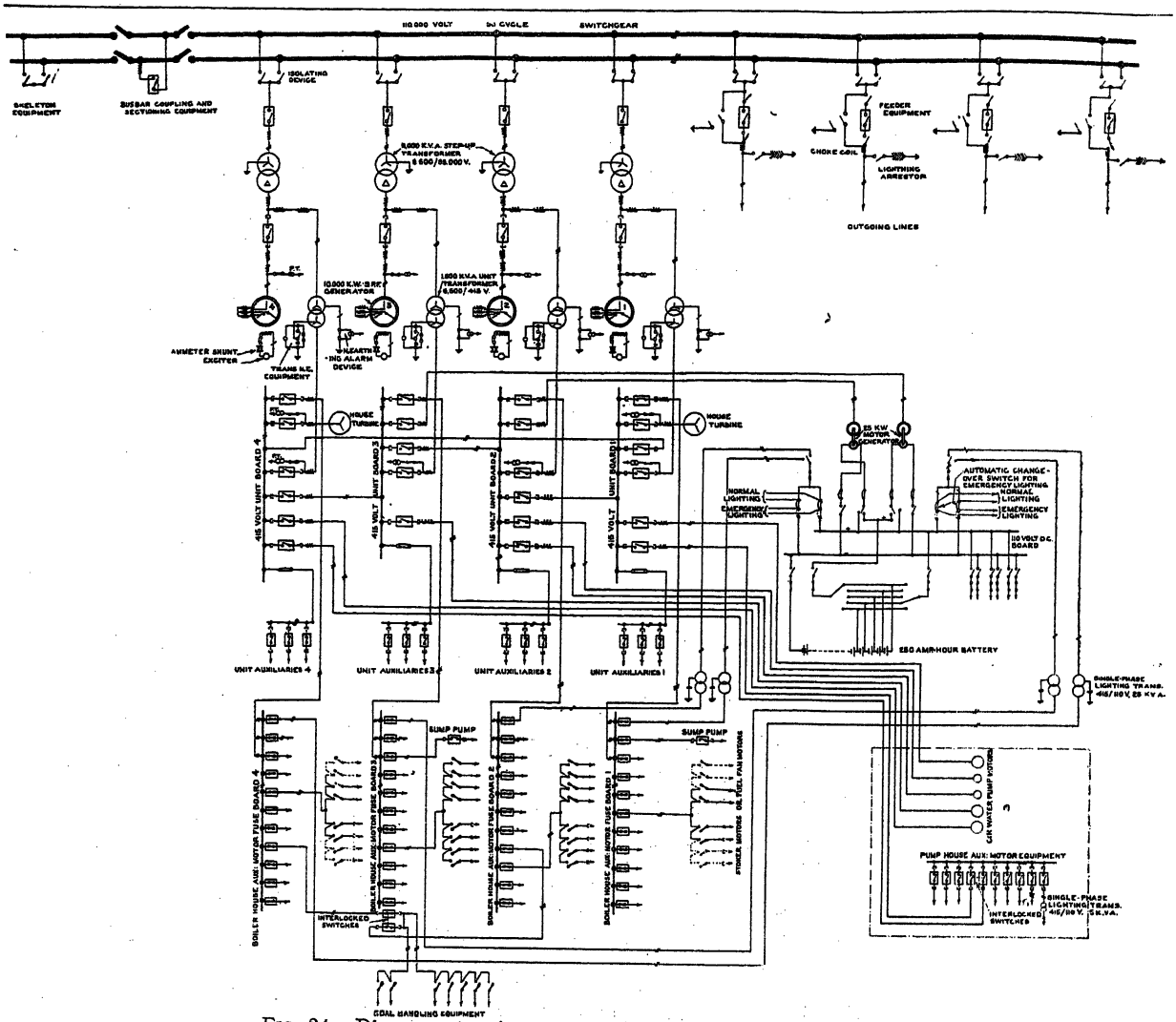


FIG. 24.—Diagram of main connections at Kalyan power station.

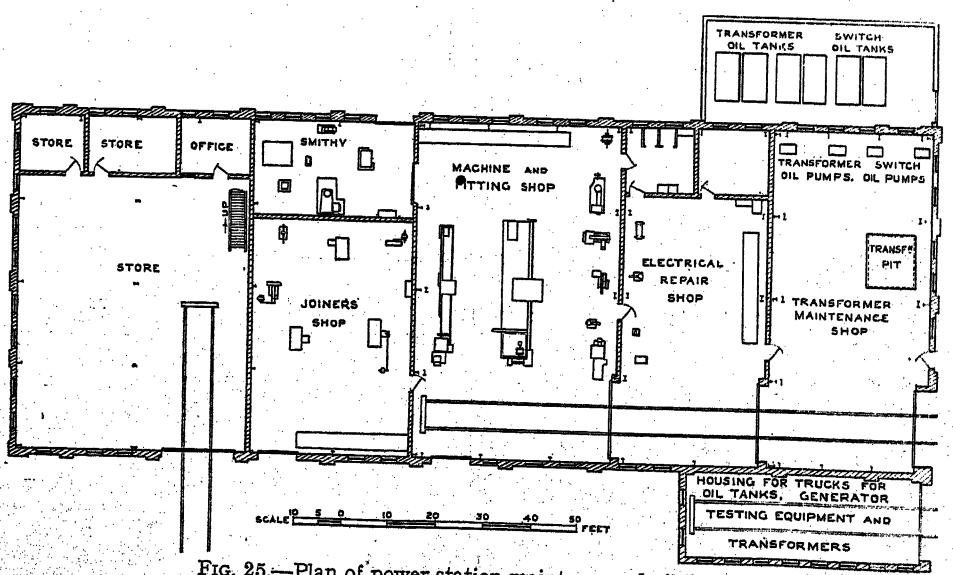


FIG. 25.—Plan of power-station maintenance building.

there are openings into the basement along both side walls, protected by iron bars, and in the south wall and both side walls there are panels of sheet-steel louvres of special design to deal with tropical rain coincident with a strong wind.

Locomotive Shops and Car Sheds.

New locomotive shops have been erected alongside the existing engine shed at Kalyan for the inspection and general maintenance of the electric locomotives. Inspection sheds for the locomotives have also been provided at Victoria Terminus and Poona, and at Igatpuri and Lonavla for the freight locomotives stationed at these points for Ghat working. A large, new car shed has been built close to Kurla for inspection and maintenance of the multiple-unit trains.

System Control.

The electrical operation of the complete scheme is under the control of the power controller, whose office is at Victoria Terminus. In this office a large wall diagram has been put up on which is shown every essential switch on the system, including the feeder switches in the power station, in the substations and track-sectioning cabins, and the isolating switches of the overhead track equipment. The office is connected by telephone with the power station and all substations, and with the locomotive shops and car sheds.

Capital Expenditure.

Suburban Scheme.

The total expenditure sanctioned on the suburban scheme was ₹s. 274 16 622 (£2 056 450 at ₹. 1 = 1s. 6d.). The actual expenditure has not been finally ascertained, but it is not likely to differ appreciably from this amount.

Main-Line Scheme.

The total estimated expenditure on which the scheme was approved was ₹s. 650 24 490 (£4 876 840). After approval was received, certain minor alterations were made, viz. 8 ballasting locomotives were omitted; 42 miles of sidings to be electrically equipped were added and modifications were made to the power-station design in order to facilitate the addition of the suburban load, if required, at a later date, with the minimum of extension and alteration. According to careful calculations prepared in April 1929, when practically all the contracts had been placed and a large part of the work had been completed, the total expenditure was estimated to be ₹s. 677 18 419 (£5 078 880). This total was made up of the following items:—

	Rupees	
(1) Locomotives	156 85 969	(£1 176 450)
(2) New running shed and alterations to existing sheds	9 20 730	(£69 050)
(3) Permanent-way equipment	209 68 317	(£1 572 620)
(4) Alterations to ways and works	6 49 000	(£48 670)
(5) Substations	99 93 623	(£749 520)
(6) Transmission line ..	63 40 591	(£475 550)
(7) Power station	131 60 189	(£987 010)
	₹s. 677 18 419	

Operation Statistics.

Train Delays.

It is still rather early to say much on the question of reliability of the electrically operated services, but the following figures may be of interest. For the suburban services during the first 8 months of the year 1931, the delays in minutes per 1 000 train-miles were as shown in Table 5.

Table 5.

Delays of Suburban Trains, January to August 1931; *minutes per* 1 000 *train-miles.*

Cause of delay	January	February	March	April	May	June	July	August
Electrical equipment	1·94	1·99	2·00	1·64	1·98	3·94	6·73	2·87
Mechanical portions	0·98	1·25	0·41	0·75	0·52	2·19	2·04	1·08
Brakes	0·64	0·23	0·16	0·19	0·20	0·52	0·52	0·42
Miscellaneous	0·11	0·12	—	0·20	0·17	0·64	0·30	0·57
Total	3·67	3·59	2·57	2·78	2·87	7·29	9·59	4·94

The number of train delays due to electric locomotive defects from January to November 1931, inclusive, are given in Table 6 (page 936).

During the six months January to June 1931, inclusive, the locomotive mileages, number of detentions, and time lost were as shown in Table 7 (page 936).

In the railway records any train detention of more than an hour due to a locomotive, or when the locomotive is unable to complete its booked run, is entered as an engine failure. The failures per 100 000 miles of steam and electric locomotives on the G.I.P. Railway during the year 1930–31 were as follows:—

Steam	3·18
Electric freight	0·45
Electric passenger ..	0·21

Additional evidence of the improvement in the services is afforded by the figures of punctuality of the trains on the Bombay division, i.e. the area between the terminus and Igatpuri and Poona, before and after electrification (see Table 8, page 936).

TABLE 6.

Number of Train Delays due to Electric Locomotive Defects, January to November 1931.

Type of defect	January	February	March	April	May	June	July	August	September	October	November
Passenger											
Electrical	4	1	5	4	3	3	3	0	0	2	2
Mechanical	2	0	0	1	1	1	0	0	0	0	1
Freight											
Electrical	1	3	1	0	2	2	0	2	3	0	3
Mechanical	3	0	2	2	1	3	0	0	1	0	1

TABLE 7.

Delays of Main-Line Trains, January to June 1931.

	Passenger trains	Freight trains
Locomotive mileage	706 484	578 924
Number of train detentions ..	25	20
Time lost (mins.) per 1 000 miles, due to locomotive defects ..	1·04	1·38

TABLE 8.

Punctuality of Trains on the Bombay Division before and after Electrification.

Period	Percentage of trains arriving right time	Percentage of trains arriving 10 minutes and under late	Percentage of trains arriving over 10 minutes late
	North-east line.		
	per cent	per cent	per cent
March 1928	42·2	18·8	39·0
March 1931	70·5	12·2	17·3
April 1928	37·2	23·3	39·5
April 1931	70·8	15·0	14·2
	South-east line.		
March 1928	68·0	19·4	12·6
March 1931	87·5	8·5	4·0
April 1928	65·8	23·0	11·2
April 1931	82·8	13·5	3·7

Traction Supply Failures.

The statement in Table 9 shows the traction supply failures and their causes during the month of October 1931. This is a fair average month, being a little better than some and not quite so good as others.

Combining the duration of each failure shown in Table 9 with the length of single-line running track affected, the minutes multiplied by miles work out at 1 784, whereas the product of the total minutes in the month and the total mileage of running track would be about 19 300 000.

Energy Consumption and Load Factor.

The average energy consumption, in terms of the power purchased from the Tata Companies, for the suburban passenger services worked by multiple-unit trains, is about 77 to 79 watt-hours per ton-mile. The energy is measured at three points, viz. (1) Dharavi receiving station from which Wadi Bandar and Kurla substations are fed by 22 000-volt underground cables, (2) Thana substation, (3) Kalyan substation. The terms of purchase are based on a unit charge as measured at these three points, plus a maximum-demand charge. The latter is at a fixed rate per kilowatt, the demand being the highest coincident quarter-hour demand during each month at the three metering points. Although the supply from the Dharavi receiving station is much greater than either of the others, the diversity is an important factor. This is clearly shown by the figures in Table 10.

The consumption of energy for main-line trains varies, naturally, according to the class of train and the gradients of the sections considered. Careful measurements have been made with a variety of passenger and goods trains, and a selection of the results are given in Table 11. In this table the consumption is given section by section in terms of watt-hours per ton-mile, the tonnage being the total weight of the train inclusive of locomotive, passengers and baggage, or load, and the energy consumption being that measured on the locomotive, inclusive of all auxiliary supplies.

With the comparatively small number of trains taking power simultaneously a high load factor at the power station is not to be expected. The figures in Table 12 (page 940), taken at random for the first and third quarters of the year 1931, show, however, that the load factor is not unreasonably low.

Regeneration.

As will be seen from the profile of the lines in Fig. 2, the opportunities for regeneration are confined to the two Ghat sections and the 25 miles between Vasind and Kasara on the north-east line. On these sections a proportion of the regenerated energy is absorbed by ascending trains, and the remainder is converted into alternating current in the substations and delivered to the transmission lines. This conversion occurs in 7 substations, and the figures in Table 13 show, as percentages, the ratios of the regenerated energy measured on the 3-phase side to the input from the transmission system for each

substation during the months March to October 1931. It should be remarked that some passenger trains are taken down the Ghat sections with their own locomotives only; that is to say, not all trains are worked regeneratively on these sections.

relation is given month by month in the last line of Table 13 (page 940). These figures show that on the average about 4½ per cent of the input to the rotary convertors is returned to the transmission lines. On the basis of traffic assumed in the working out of the scheme, the

TABLE 9.

Traction Supply Failures During October 1931.

Date	Duration of failure	Sections affected	Length of single running track affected	Cause of failure
	minutes		miles	
1st	—	Nil	—	—
2nd	—	Nil	—	—
3rd	1	Up goods yard at Kalyan	Nil	Unknown
4th	—	Nil	—	—
5th	3	Both lines, Lonavla to Poona	78	Voltage fluctuation due to tripping-out of both south-eastern transmission lines at Karjat
	1	Both lines, Thansit to Kasara	28	
	1	Up line, Kalyan to Vasind	15	Unknown
	1	Up line, Kalyan to Titvala	5	
6th	2	Both lines, Badlapur to Malavli	86	Tripping-out of south-eastern transmission line at power station
	3	Both lines, Malavli to Poona	68	
7th	2	Both lines, Badlapur to Poona	154	North-eastern transmission line tripped out at power station owing to boat mast fouling line at Titvala river crossing
	3	Both lines, Titvala to Igatpuri	90	
8th	1	Both lines, Lonavla to Kamshet	20	Feeders tripped out due to lightning
9th	—	Nil	—	—
10th	—	Nil	—	—
11th	—	Nil	—	—
12th	—	Nil	—	—
13th	—	Nil	—	—
14th	—	Nil	—	—
15th	2	Up local, Wadi Bandar to Terminus	1¼	Defective multiple-unit train
16th	—	Nil	—	—
17th	—	Nil	—	—
18th	—	Nil	—	—
19th	—	Nil	—	—
20th	—	Nil	—	—
21st	46	Up line Titvala to Kalyan,	5	Lightning-arrestor gap at Titvala track cabin short-circuited by rat
	145	Up line, Titvala switch No. 2 to Titvala cabin	1¾	
22nd	—	Nil	—	—
23rd	—	Nil	—	—
24th	1	Down local, Thana to Vikhroli	6	Defective multiple-unit train
25th	—	Nil	—	—
26th	—	Nil	—	—
27th	—	Nil	—	—
28th	—	Nil	—	—
29th	—	Nil	—	—
30th	—	Nil	—	—
31st	—	Nil	—	—

The figures for each substation are some indication of the effect of the various gradients, but in attempting to form any idea as to the monetary value of the regenerative feature in the design of the freight locomotives it is necessary to consider the relation between the total input to all the main-line substations and the total energy returned to the transmission system. This

total input would be about 60 000 000 kWh per annum. The energy returned to the high-tension lines would therefore be about 2 700 000 kWh per annum. The value of this saving, quite apart from further saving in respect of regenerated energy which is absorbed by other trains without being converted at the substations, is ample to pay the capital charges on the extra cost

TABLE 10.

Load Factor and Diversity Factor of Supply to the Suburban Substations.

Period	Four weeks ending 1st December, 1928	Four weeks ending 29th December, 1928
Units (kWh) delivered to all substations*	3 517 350	3 859 850
Summation of individual ¼-hour maxima (kW) ..	12 960	14 544
Coincident ¼-hour maximum (kW)	10 224	11 520
Diversity factor	1·26	1·26
Load factor, per cent ..	51·0	49·5

* The units delivered include about 10 per cent for the locomotive and carriage and wagon works.

of equipping the 41 freight locomotives with exciters and additional switchgear.

A further important advantage arising from the use of regenerative braking, especially on the Ghat sections, is the reduction in brake-block renewals.

Table 14 (page 940) gives a representative indication of the brake block renewals at the running sheds.

It will be seen that without regeneration the consumption of brake blocks is in the neighbourhood of 7 per 1 000 locomotive-miles, and with regeneration 3·5 blocks per 1 000 locomotive-miles, the difference being clearly due to the reduction in consumption on the Ghat sections.

Locomotive Mileages.

From the remarks in the early part of this paper on passenger and goods traffic it will be clear that the electric locomotives, especially those for the freight trains, are not working to their full capacity. The locomotive mileages for the 12 months November 1930 to October 1931 are given in Table 15 (page 940).

According to the link working which was put into force on the 1st September, 1931, the whole of the main-line passenger traffic between Bombay and Igatpuri and Poona requires 15 passenger locomotives, each going through the complete schedule once every 15 days. During this period the mileage, apart from light mileage, is 3 930, equal to an average of 262 per day, the maximum on any one day being 436, made up of 4 separate runs. It is clear that the 24 locomotives are capable of dealing with a good deal more traffic, even when all necessary allowance has been made for spares, specials, and overhaul.

Operation and Maintenance Costs.

Many parts of the complete installation have only recently passed out of their respective maintenance periods; it is, therefore, too soon to obtain properly representative costs of operation and maintenance. The following figures relating to the main-line portion of the scheme, specially prepared for this paper by the Chief Transportation Superintendent's Department, and based on ascertained costs for the months of December 1931, and January and February 1932, will be of interest.

(1) *Locomotive oil and stores and running shed charges.*		per engine mile
Passenger engines		1·46 annas
Goods engines		2·42 annas
(2) *Locomotive repairs.*		
Passenger engines		1·14 annas
Goods engines		1·88 annas
(3) *Wages of locomotive crews.*		
Passenger engines		4·64 annas
Goods engines		4·99 annas
(4) *Substation attendants* in main-line substations		per annum Rs. 1 66 150
(5) *Substation maintenance* (main-line substations and proportion of plant in suburban substations ..		Rs. 84 890
(6) *Stores and lubricants for substations*		Rs. 3 140
(7) *Labour and supervision for maintenance of permanent-way equipment and transmission system*		Rs. 1 51 310
(8) *Materials for maintenance of permanent-way equipment and transmission system*..		Rs. 21 500
(9) *Establishment charge*		Rs. 9 860
(10) *Staff for control of electrical system* ..		Rs. 14 620
(11) *Establishment charge*		Rs. 1 040
(12) *Additional expenses of headquarters staff*		Rs. 20 600
(13) *Rental of new telephone and control lines*		Rs. 14 400

OPERATING EXPERIENCE.

Multiple-Unit Trains.

On the whole the multiple-unit train equipments have given satisfactory service. In the early stages some trouble was experienced with the armature windings of the main motors, which was accentuated by the lack of adequate facilities for repairs in the railway shops. Improved methods of insulating the coils were adopted, and with better arrangements for maintenance the number of failures has been greatly reduced. Thus, for the first 8 months of 1931 there were only 13 armature failures, one of which was due to the breakage of the shaft. There have been rather more than the usual number of hot armature bearings. With careful maintenance and attention to lubrication routine this trouble can be kept down, as shown by the statistics of certain months, but at times, especially during the monsoon, the number of failures is still abnormally high. The principal trouble, however, has been an unusual succession of gear failures.

The original gears provided with all the motors of the first 38 motor-coaches were made by a French firm, who had previously supplied satisfactory gears for the Midi Railway. During inspection before shipment to Bombay certain undesirable features were observed, and acceptance was withheld, but in order not to hold up the whole contract and delay the start of operations the gears were shipped, and if they had given satisfactory results in service they would have been accepted. After about

TABLE 11.

Energy Consumption of Main-Line Passenger and Goods Trains.

Class of train	From	To	Total weight, including locomotive and load	Number of axles	Section Bombay–Kalyan Length = 31·75 miles Difference of level = 0 ft.					Section Kalyan–Kasara Length = 41·9 miles Difference of level = 924 ft.					Section Kasara–Igatpuri Length = 8·6 miles Difference of level = 960 ft.				
					Number of			Average speed (excluding stops)	Watt-hours per ton-mile	Number of			Average speed (excluding stops)	Watt-hours per ton-mile	Number of			Average speed (excluding stops)	Watt-hours per ton-mile
					Starts	Stops	Checks			Starts	Stops	Checks			Starts	Stops	Checks		
			tons					m.p.h.					m.p.h.					m.p.h.	
Mail	Bombay	Igatpuri	415	38	1	1	2	51·5	36	1	1	1	51·2	48·5	1	1	1	22·4	154
Mail	Igatpuri	Bombay	411	34	1	1	1	44·4	25	1	1	0	49·4	15	—	—	—	—	—
Mail	Igatpuri	Bombay	457	38	2	2	0	40·5	24·5	1	1	0	43·3	10	—	—	—	—	—
Express passenger	Bombay	Igatpuri	414	38	5	5	1	31·8	36	1	1	0	52·4	47	1	1	0	26	154
Express passenger	Igatpuri	Bombay	427	38	5	5	1	36	36	2	2	0	46·5	11	—	—	—	—	—
Stopping passenger	Bombay	Igatpuri	453	46	5	5	0	36	35	12	12	0	30·6	50·5	—	—	—	—	—
Stopping passenger	Igatpuri	Bombay	511	78	5	5	0	35·3	36	11	11	0	34·5	28·5	5	5	0	17·2	— 52
Through goods	Kalyan	Igatpuri	1 090*	132	—	—	—	—	—	2	2	0	26·2	41	1	1	0	13·6	121
			1 210†	138															
Empties	Kalyan	Igatpuri	835*	136	—	—	—	—	—	3	3	0	28·9	49	1	1	0	10·9	131
			955†	142															
Through goods	Igatpuri	Kalyan	1 804‡	142	—	—	—	—	—	1	1	1	25·8	8	5	5	0	10·3	— 41
			1 684§	136															
Goods	Igatpuri	Kalyan	1 815†	142	—	—	—	—	—	7	7	0	17·2	10	5	5	0	8·9	— 37
			1 695§	136															
Goods	Kalyan	Kurla	1 654	128	2	2	0	25·2	19	—	—	—	—	—	—	—	—	—	—

Class of train	From	To	Total weight, including locomotive and load	Number of axles	Section Bombay–Kalyan Length = 31·75 miles Difference of level = 0 ft.					Section Kalyan–Karjat Length = 28·9 miles Difference of level = 144 ft.					Section Karjat–Lonavla Length = 17·2 miles Difference of level = 1 867 ft.					Section Lonavla–Poona Length = 39·75 miles Difference of level = 217 ft.				
					Number of			Average speed (excluding stops)	Watt-hours per ton-mile	Number of			Average speed (excluding stops)	Watt-hours per ton-mile	Number of			Average speed (excluding stops)	Watt-hours per ton-mile	Number of			Average speed (excluding stops)	Watt-hours per ton-mile
					Starts	Stops	Checks			Starts	Stops	Checks			Starts	Stops	Checks			Starts	Stops	Checks		
			tons					m.p.h.					m.p.h.					m.p.h.					m.p.h.	
"Deccan Queen"	Bombay	Poona	391	28	1	0	1	50·2	31·5	0	1	1	52·5	29	1	1	1	26·4	124	1	1	2	50·8	26·5
"Deccan Queen"	Poona	Bombay	391	28	0	1	3	45·4	34	1	0	0	54·2	28	—	—	—	—	—	1	1	2	52	36
Mail	Bombay	Poona	406	38	1	1	2	45·4	28	1	1	0	51	29·5	3	3	3	13·0	—	2	2	2	47·7	21
Mail	Poona	Bombay	377	34	1	1	2	44·3	31·5	1	1	1	49·6	31·5	4	4	0	21·5	— 60	2	2	3	46·8	38
Stopping passenger	Bombay	Poona	574¶	—	6	6	1	36	39	6	6	0	33·4	52	5	5	0	19·5	—	10	10	0	35	40
			446**																					
			458††																					
Stopping passenger	Poona	Bombay	470	46	5	5	0	35·2	33	6	6	0	36·2	28·5	—	—	—	—	—	10	10	0	32·3	38
Through goods	Kalyan	Poona	1 113	116	—	—	—	—	—	1	1	0	28·9	23	2	2	0	12·2	123	2	2	2	22·7	16
Through goods	Kalyan	Poona	1 134	92	—	—	—	—	—	1	1	0	29·4	21	1	1	0	12·9	120	2	2	0	28·7	16
Section goods	Kalyan	Poona	788**	—	—	—	—	—	—	5	5	0	22·5	34§§	1	1	0	12·6	125	2	2	0	30·7	17
			1 200††																					
			1 120‡‡																					
Through goods	Poona	Kalyan	1 435	132	—	—	—	—	—	2	2	1	21·7	17	4	4	0	13·7	— 66	1	1	1	29·8	26

* Kalyan–Kasara. † Kasara–Igatpuri. ‡ Igatpuri–Kasara. § Kasara–Kalyan. ¶ Bombay–Kalyan. ** Kalyan–Karjat.
†† Karjat–Lonavla. ‡‡ Lonavla–Poona. §§ Includes some shunting at intermediate stations.

TABLE 12.

Output from Kalyan Power Station, and Load Factor.

Quarter	January–March, 1931	July–September, 1931
Units (kWh) sent out ..	11 586 770	9 573 600
Half-hour maximum (kW)	12 360	10 500
Load factor, per cent ..	43	41·7
Maximum observed load on generators, kW ..	18 000	16 400

12 months' service, however, breakages of gear wheels and pinions began to occur, and from June 1926 onwards these breakages continued at an accelerated rate. At the end of that year it was decided that all the gears in use on the harbour branch must be replaced, and subsequently, in May 1927, as those in use on the other suburban lines were also failing at an increasing rate, all the original gears were condemned.

The principal particulars of the French gears were as follows:—

Tooth design: Sunderland form—2½ dia. pitch.
Gear-wheel construction: Shrunk-on rims.
Steel composition: C 0·25, Si 0·56, S 0·06, P 0·033, Mn 0·37, Ni 2·62, Cr 0·71.

Owing to labour troubles in this country, the order for gears and pinions to replace the first set, and to equip the remaining 15 motor coaches, was placed with a Continental firm of steel-makers. With the exception of the first 12, which were of chrome-nickel steel, the new gear-wheels were, on the recommendation of the steel-makers, of manganese-silicon steel, and all the new pinions and gears were made with teeth of the Maag form, calculated to give an increase in strength of about 23 per cent compared with those of the Sunderland form.

The particulars were as follows:—

Tooth design: Maag form—2½ dia. pitch.
Gear-wheel construction: Shrunk-on rims.
Steel composition:—

	C	Mn	Ni	Cr	Si	Mb
Pinions						
First 12 ..	0·264	0·505	2·79	0·99	0·177	0·293
Remaining 200	0·35	0·35	5·30	1·20	0·30	—
Gear rims						
First 12 ..	0·279	0·57	2·80	1·00	0·170	0·297
Remaining 200	0·50	1·30	—	—	0·70	—

Unfortunately, the second set proved no more satisfactory than the first. The first 12 pinions were too soft, and after 3 had failed the other 9 were taken out of service. In October 1927, one of the manganese-steel gear rims broke after running about 10 500 miles. This was followed by other similar breakages and by the end of June 1928 there had been 30 failures of the gear-wheel rims. By this time it was evident that whatever

TABLE 13.

Regenerated Energy returned to the Transmission System, as Percentage of Input to Substations, 1931.

Substation	March	April	May	June	July	August	September	October
Vasind	1·5	3·1	1·4	2·1	1·2	1·8	1·0	1·1
Thansit	3·2	3·9	3·1	2·0	—	1·6	1·9	2·1
Kasara	7·2	9·1	8·8	7·4	6·5	6·0	4·5	5·4
Igatpuri	12·1	12·3	13·6	11·0	9·8	9·5	7·2	10·0
Karjat	5·0	5·2	4·6	4·3	5·2	4·3	4·2	3·7
Thakurvadi	17·0	16·3	15·9	16·1	12·1	10·9	10·8	13·2
Lonavla	4·5	4·8	5·4	4·8	4·8	4·0	3·4	4·4
All main-line substations	4·9	5·6	5·1	4·8	4·1	4·0	3·5	4·3

TABLE 14.

Consumption of Brake Blocks on Electric Freight Locomotives, with and without Regeneration.

	Lonavla	Igatpuri	Kalyan	Total	Engine mileage
Without regeneration from 12/7/30 to 16/8/30	30	58	294	382	55 000
With regeneration from 25/4/31 to 27/6/31	0	43	360	403	115 000

TABLE 15.

Electric Locomotive Mileages, November 1930 *to October* 1931.

Period	November 1930 to April 1931	May 1931 to October 1931	November 1930 to October 1931
Average mileage per locomotive of 24 passenger locomotives ..	29 195	30 847	60 042
Average mileage per locomotive of 41 freight locomotives ..	14 814	11 430	26 244

the cause, these manganese-steel gears could not be relied on to stand up to the service conditions. After much discussion it was decided to replace them all and to revert to chrome-nickel steel. In order to save delay, 36 gears were put in hand, the blanks being supplied by Messrs. Cammell Laird and Co. of their "Non-Brit" grade of nickel-chrome steel to B.S.S. No. 1286 (Part 3) with a small added percentage of molybdenum, and the balance of the 216 were replaced by the Continental firm, the teeth being cut, as before, by the English Electric Co. in their own works. In both cases the gear-wheels were solid, i.e. they were not made with shrunk-on rims and the Maag form of tooth was retained, with 2½ dia. pitch. The Continental blanks were of heat-treated steel of the following composition: C 0·38, Mn 0·35, Si 0·24, P 0·022, S 0·028, Ni 2·64, Cr 1·20.

These solid gears were put into service with the 200 pinions of chrome-nickel steel from the Continental firm, which had not then shown any signs of premature failure. Subsequently, however, the pinions began to crack and break in considerable numbers, generally after running about 150 000 miles, as guaranteed, and in a few cases damaged the gear-wheels with which they were working. Apart from the failures associated with pinion breakages, only 3 of the 200 solid chrome-nickel gear-wheels have so far broken, 2 of these being from the Continental firm mentioned above, and one from the Cammell Laird delivery. Up to the middle of last November 78 pinions had failed or had been removed. These are being replaced, when necessary, from a stock of 100 purchased by the railway, 50 from Messrs. Wiseman, 50 from the Tool Steel Gear and Pinion Co. of Cincinnati, and more recently by a further 50 from the English Electric Co.

The trouble with gears, as shown by the foregoing abbreviated account, has been due to a combination of unfortunate circumstances. It cannot be regarded as typical of suburban electrification in India, as on the Bombay, Baroda and Central India Railway, on which the operating conditions are practically identical, there has not up to the present after 4 years of working been a single failure of either pinion or gear-wheel. On a conservative estimate the life of the pinions will be at least 500 000 miles and of the gears 750 000.

Freight Locomotives.

In any scheme of main-line electrification the behaviour of the locomotives in service is more important, and therefore of more interest, than that of any other section of the complete electrical installation apart from the overhead line. A failure in a locomotive will probably cause more delay to traffic than, for example, a substation breakdown, where, if a rotary convertor fails, the spare set can be put into service immediately, and nothing is noticeable beyond a drop in the line voltage for a few minutes.

It is therefore very gratifying to all concerned that in this scheme it can be recorded that the locomotives have been almost entirely free from serious trouble. This is reflected in the figures of train delays mentioned on page 936. There have, of course, been a few minor difficulties, such as inevitably occur when plant or apparatus containing novel features in the detailed design is first put into service, but it can be said that if there had been no derailments and no troubles attributable in one way or another to lubrication, three-quarters of the work in the locomotive shops beyond that of the ordinary routine inspection and maintenance would have been eliminated. The derailments have been comparatively numerous, and in practically every case have been due to split points or spread rails; in no case was the derailment due to any cause inherent in the locomotives.

Electrically the freight locomotives have a very good record. In the 3 years from May 1928 to June 1931 only 4 motors have been removed from locomotives for motor faults, and there have been no bearing failures in service. During the same period there have been about 20 instances of flashing-over—some very slight—and nearly half of these were traced to causes outside the motors or to foreign bodies such as tools left in the motors. In most cases the flash-overs were not noticed until the locomotive came in for inspection. In the auxiliary machines one blower motor and one compressor motor have failed, and one or two axle generators were damaged by running through floods. There have been no breakages of gears or pinions, and the control apparatus has given no trouble. The lightning arrestors have not been satisfactory, but under the circumstances this has not been important.

Mechanically the locomotives have been singularly free from trouble in service, and the principal points which have called for attention in maintenance have been (1) jackshaft bearings, (2) crank pins and coupling-rod bearings, (3) breakages of laminated bearing springs, and (4) breakages of side bearer springs.

The total output of the four 650-h.p. motors is transmitted to the driving wheels by 2 jackshafts which run in 4 bearings. The tractive effort of the locomotive occasionally reaches 80 000 lb., and as the transmission is by means of cranks at right angles, each of the 4 jackshaft bearings is at such times subjected to a periodic force of about 80 000 lb. During the first year or so of operation many of these bearings were found on examination to have cracked or dragged white metal, indicating that at some time there had been overheating, though very few failures occurred in service. After prolonged investigation it was concluded that the system of lubrication was responsible. Immediately after the oil wells were filled, the bearings were flooded with oil to such an extent that a large proportion passed out into the gear case instead of returning to the well. After a comparatively short time this loss of oil led to insufficient lubrication of the bearing and consequent overheating. The trouble could be overcome by frequent refilling of the reservoir, but this was not considered satisfactory, and after many trials it was decided to make a modification in the design in order to restrict the supply of oil to the bearing when the reservoir was full. This alteration is being made in all locomotives as opportunity offers, and it is expected that it will not only eliminate the trouble but also result in a great saving of oil. Before the alteration, the quantity used for the 4 bearings, with careful supervision, was about 20 lb. per 1 000 locomotive-miles; after the alteration on the selected locomotive the consumption was 10 to 11 lb.

A few failures occurred in the big-end bearings of the

coupling rods and the side-rod bushes. Insufficient lubrication was mainly responsible, and, possibly in one or two instances, rust on the pins which escaped notice when the locomotives were assembled in Bombay.

A certain number of plates in the laminated bearing springs have broken. The cause of the breakages is not definitely known; the margin of safety in the material is probably insufficient. Each spring consists of 12 $\frac{1}{2}$-inch plates, and of the total number of 5 904 plates 254 had broken by the end of February 1931. The great majority of breakages occurred in plates numbered 8, 9, 10, and 11, counting downwards. A few springs of $9\frac{5}{8}$-in. plates are being tried in place of those originally supplied.

The side-bearer springs, which transmit part of the weight of the body to the trucks, have had to be replaced. These springs were of the " Parabo " type, and it was found necessary to use a better quality of spring steel than that originally provided. The new springs are of the helical type instead of the " Parabo."

The following notes on the intermediate overhaul of one of the locomotives after running 59 209 miles will give an idea of the maintenance work required.

Main Motors.—2 cracked insulators in the brush-gear renewed, and 2 small pieces of white metal removed from one of the armature bearings and renewed; otherwise nothing required beyond a general cleaning.

Axle Generators.—Cleaning only.

Auxiliary Motors, etc.—The commutator of No. 2 blower motor required skimming up; otherwise nothing required.

Unit Switches.—The arcing cheeks on 8 switches were renewed; main contacts cleaned up; 5 valve stems found to be slack and were replaced; piston leathers greased and refitted; pins and joints lubricated.

Group Switches.—Two pairs of power contacts renewed; otherwise everything in good order.

Main Resistances.—Bolts tightened up; no broken grids found.

Pantographs.—All parts cleaned and lubricated, and piston leathers of No. 1 pantograph renewed.

Compressors.—Valve seatings reground, everything else in good condition.

Exhausters.—No replacements necessary; light deposits of carbon removed; valves and lubricators cleaned.

Jackshaft Bearings.—All 4 bearings were in bad condition, and had to be remetalled.

Axle Bearings.—All in excellent condition; no renewals necessary.

Crankpins.—All required regrinding.

Big-End and Side-Rod Bushes.—Two big-end and 5 side-rod bushes remetalled.

Wheels, Tyres, and Axles.—Axle journals and wheels in sound condition; tyre wear as follows*:—

	Maximum in.	Minimum in.
Flange	0·100	0·008
Radius at root of flange ..	0·110	0·045
Tread	0·130	0·120

* In connection with tyre wear a recent examination was made of a locomotive which had run 100 899 miles; the figures of wear were as follows:—

	Average in.	Maximum in.	Minimum in.
Flange	0·116	0·232	0·04
Radius at root of flange	0·19	0·29	0·126
Tread	0·185	0·205	0·122

Main Springs, Cotters, and Pins.—Three main springs were found with one leaf broken in each; spring hanger cotters slightly worn and made up by welding; equalizing pins badly worn owing to insufficient lubrication.

Gears and Pinions.—All gears and pinions in excellent condition.

In regard to experience in service the operation of heavy trains on the Ghat sections may be mentioned. As already stated, trains of 1 600 tons (excluding locomotives) are taken down the 1-in-37 gradients by 2 freight locomotives. The train is controlled by regenerative braking, which is working very satisfactorily. Before this method of working was put into force, the trains were controlled by the train and locomotive brakes, and when, as frequently happened, the train brakes were not in good condition, the brake blocks on the locomotives were subjected to very severe treatment, and in fact became so hot that they were deformed and had to be renewed after a few trips.

On the uphill journey when trains of 1 000 tons are hauled by one locomotive in front with another pushing in the rear, the conditions of operation are complicated by the necessity for frequent unscheduled stops on the gradient on account of track repairs. The two locomotives are not in sight of each other, and it is not easy to signal from one to the other by whistle. The control of the two locomotives in unison when switching on and off calls for a good deal of skill, only acquired by extended experience. The only indications that the driver in the rear has that the driver in front is switching off are the movements of the voltmeter, ammeter, and the vacuum gauge. Any lack of attention or skill in handling the controller of the rear locomotive in these circumstances causes a surge to travel along the train, with every chance of a breakage in a wagon drawbar or coupling. Such breakages were not always attributable to flaws in the drawgear, and were more frequent when trains were hauled uphill at the speed corresponding to the parallel grouping of the locomotive motors (about 18 m.p.h.) than at half speed with the motors in the series-parallel grouping. With sufficient experience and proper attention to method in driving, the risk of breakage of sound couplings is negligible, but in view of the present small volume of traffic, and in order to reduce the fluctuations in the demand on the power station, the working of these heavy trains up the Ghat sections is restricted for the time being to half speed.

Passenger Locomotives.

Mention has already been made of some of the operating characteristics of these locomotives, in particular their riding qualities and their ability to work in parallel with the freight locomotives. Before referring to details of maintenance, a few figures may be quoted of a special test in which a single locomotive was called on to haul a train of 14 bogie coaches (total weight, including the locomotive, 582 tons) from Bombay to Kasara at the foot of the Thull Ghat. Reference to Fig. 2 will show that between Kalyan and Kasara there are long stretches of 1-in-100 rising gradient, and, although this gradient does not call for any unusual effort from the locomotive for a non-stop train, the conditions are rather severe with a train stopping at all stations and sometimes

between stations on sharp curves on the gradient. The train in question stopped 4 times between Bombay and Kalyan, and 12 times between Kalyan and Kasara, viz. at 10 stations and 2 outer signals. The schedule running time for a stopping train of normal weight is 70½ minutes; the actual time of the test train was 84¾ minutes, and would have been about 76 minutes without the 2 additional signal stops. (It may be mentioned that as the result of electrification the total timing of the normal stopping train between these points had been reduced by about one hour compared with steam working.) During the special test the starting current per motor was occasionally as much as 550 amperes, and no slipping occurred, except at Victoria Terminus. At each start after leaving the terminus, sand was applied to all driving wheels until the train moved off, after which only the leading drivers were sanded. On arrival at Kasara temperatures were taken and were as follows: Air temperature (intake to blower) 34° C., main motor armature 74° C., commutator 84° C., main resistances 170° C.

Apart from the comparatively unimportant details mentioned below, the experience with the passenger locomotives has been very satisfactory. On the electrical side the only troubles worth mentioning have been failures of lightning arrestors, and flashing-over of the main motors. The former was under the circumstances not important, and the damage done by flashing-over was in most cases negligible. As usual, the causes of flash-over were difficult to determine; sometimes a minor fault in the control circuits or group switches might be responsible, but a more probable factor is the use of an unsatisfactory grade of brush which leads to deterioration of the commutator surface. Satisfactory brushes have been found with a life of 150 000 to 160 000 miles per inch of wear, and the trouble of flashing-over has been practically eliminated.

The commutators of the blower motors have shown a tendency to sparking and blackening. This is probably due to dust being drawn in from the floor of the locomotive.

On the mechanical side of the electrical equipments the only troubles that have occurred in 3 years have been bearing failures due to faulty lubrication. These have occurred for the following reasons:—

(1) Entry of water into the gear case when the locomotives were working through deep floods in 1930. Several bearings on one locomotive failed.

(2) Breakage of the drive from the wheels to the Wakefield lubricator which supplies the motor bearings. Several bearings on 4 locomotives failed.

(3) Faulty remetalling of bearings previously damaged.

(4) Unknown cause. Two bearings on one motor failed.

At one time there were a crop of bearing troubles in the main drive, i.e. the combination of pinions and gears inside the gear case. The bearings of the intermediate gears and the quill bearings failed, owing to an insufficient supply of oil. As the result of a thorough investigation it was found that the oil used in the gear case was liable under certain conditions to become so viscous that it ceased to flow from the oil pockets into the bearings. The trouble has been overcome by using a lighter oil, but more care is needed in keeping the gear cases oil-tight, otherwise the loss of oil may be considerable.

Of the mechanical parts there has been very little to criticize. The principal novelty, viz. the so-called "Winterthur" flexible drive, has been entirely satisfactory. In the driving wheels on the sample locomotive a number of cracked spokes were observed in the early days, and ultimately the wheels were replaced by others having slightly thicker spokes. The auxiliary bearing springs of the "Parabo" type, after numerous breakages, have been removed.

In September 1931 the first Metropolitan-Vickers passenger locomotive was brought into the shops for intermediate overhaul after having run 147 648 miles. The report of the examination is too long to quote in detail, but it may be said that the locomotive was found to be, both electrically and mechanically, in very good condition. Repairs and replacements were confined to a few parts, such as Armstrong oilers; slippers on 2 axle boxes; 5 of the 6 quill bearings remetalled; the teeth of one gear wheel trimmed up with a file (the damage had been caused by a 4½-in. nail and a ½-in. spring washer found in the gear case); one plate in one main bearing spring replaced; main spring buckle pins, hangers and cotters made up to size by welding; pantograph parts; main motor commutators skimmed (loss of diameter $\frac{1}{32}$ in. on 5 motors, $\frac{1}{16}$ in. on the 6th); auxiliary motor commutators skimmed; a few piston leathers and arc cheeks in the unit and group switches replaced; bogie and pony wheel tyres turned. The wear of the driving-wheel tyres which had not run the full mileage (53 064, 50 688, and 99 055 respectively) was not sufficient to make turning necessary.

As the result of this intermediate overhaul attention was directed to a number of points in the routine maintenance, such as the lubrication of pantograph joints and a number of other parts which have suffered slightly from being allowed to get dry, and the use of the right kind of grease for piston leathers. With the improvement that will result from these alterations in the routine maintenance it should not be necessary to bring the locomotives in for overhaul more frequently than every 200 000 or 250 000 miles.

The men-hours needed for this overhaul were as follows:—

"A" grade chargemen	400 hours
"C" grade chargemen	244 ,,
Leading electrical fitters	470 ,,
Mechanical fitters	1 312 ,,
Assistant fitters	1 536 ,,
Crane drivers	224 ,,
Machine men	64 ,,
Coppersmiths or welders ..	80 ,,
Coolies	1 888 ,,

The total cost of labour and material, including Rs. 310 (£23 5s.) for remetalling the quill bearings, was Rs. 2 830 (£212).

The average consumption of oil for all purposes per 1 000 locomotive-miles is about 50 to 55 lb.; small modifications in hand will bring this down, and in future it should not exceed 40 to 45 lb.

Track Equipment.

As already mentioned, a good deal of trouble was caused in the early days by the unfortunate habit of crows of carrying about lengths of wire and building nests with them, especially in the braced corners of the track structures. The liability to produce short-circuits on this account was overcome by fitting adequate bird guards and by introducing certain revisions of design into subsequent instalments of the equipment.

After about two years' operation of the electric services on the harbour branch a careful examination was made of all the track structure foundations, and it was found that a few concrete blocks in more or less permanently damp ground showed signs of cracking. To investigate the extent of the damage one or two blocks were pulled up and broken and a certain amount of corrosion of the embedded bolts was then evident. In one case the bolts had been nearly eaten through about half-way down; in others the damage was slight. As the result of the general investigation it was considered that no immediate steps were necessary to safeguard the position beyond the fitting, in certain places, of spark-gaps in the earth connection between the structures and the rails, as mentioned above. Since then, all structure foundations have been carefully observed from time to time, but no evidence of any serious corrosion has been seen, nor has there ever been a structure failure on this account.

Apart from these points, it can be said that the complete equipment has proved very satisfactory. In particular, one point may be mentioned, viz. there has been no difficulty about the collection of heavy currents at high speeds. Before any substantial progress was made with the main-line scheme, this point was thoroughly tested with an experimental train consisting of a steam passenger locomotive, a pantograph coach, and an observation coach from which the working of the pantograph could be seen and which carried all necessary instruments for indicating and recording the current collected, the line voltage, and the speed. The tests were made on a suitable section of the suburban lines, on which the contact wire has an area of 0·25 sq. in.; part of the section selected is straight and part on a curve of one-mile radius. Various tests were made, including the collection of 750 amperes at 1 500 volts at 70 to 75 m.p.h., and 1 000 amperes at 75 to 80 m.p.h. In each case a single pantograph was used, with a pressure of 28 lb. against the contact wire. Observation showed that collection in both cases was very satisfactory, especially if the fittings attached to the contact wire, in particular the steady arms, were made as light as possible. With long steady-arms there was a tendency to spark at each pull-off, but this was not noticeable where short arms had been substituted. A certain amount of sparking was experienced at special places such as cross-overs and knuckling points, but this is inevitable and is not important. In the designs finally adopted certain modifications made to the knuckling points have considerably improved the collection.

In view of apprehensions in some quarters in this country that extensive alterations to the signalling system are necessary where a line is electrified, owing to the usual signals being obscured by the track structures, it is worth mentioning that no signals on the G.I.P. Railway had to be altered for this reason. It was found that although at first drivers had a little difficulty in picking up the signals, they soon became accustomed to the different appearance of the track and knew exactly where to look for the semaphore arms and the lights.

Substations.

During the first year of operation of the suburban electrification the converting plant and switchgear in the Wadi Bandar and Kurla substations were subjected to very severe treatment on account of the short-circuits, due mainly to crows. Considerable damage was caused to the commutator risers of the rotary convertors by the flames resulting from a flash-over, although they were protected by an insulating barrier. It was ultimately found that the trouble was caused by the flames, which were blown horizontally along the commutator surface away from the armature, being drawn down and inwards through the annular opening round the shaft at the end of the commutator by the fan action of the risers. When this annular opening was closed, the trouble ceased. Subsequent machines were built with commutators of the same diameter as the armatures.

The possibility of trouble due to vermin has already been mentioned. An instance of this occurred in the Kalyan substation in December 1928, when the 1 500-volt busbar arced over to the wall of the busbar chamber. There is little doubt that the cause was a mouse, which was found after the burn-up in the chamber.

A rather more serious breakdown occurred in the same substation in May 1929, when, due to the failure of one of the 1 500-volt machine circuit-breakers to clear the arc formed on opening, and the consequent damage to the auxiliary circuit connections in the cubicle, the two rotary convertors of that set lost their separate excitation, the high-tension switch opened, and both armatures stopped and then ran away in the reverse direction of rotation. Fortunately the rest of the plant in the substation was not damaged in any way, and service was maintained by the spare set during the repair of the armatures in this country. Following this breakdown, certain modifications to the general design and detailed arrangement of the 1 500-volt switchgear were made, consisting chiefly in building the busbar chamber and the cubicles of concrete, sealing the chamber from the cubicles, and shielding the auxiliary circuits from the main circuit breakers. A negative circuit breaker was also inserted, as already mentioned.

In the eleven substations on the main-line sections beyond Kalyan there has been practically a complete absence of trouble; this must be regarded as very satisfactory, considering the special features of extra-high-voltage supply, regenerating convertors, automatic operation, and supervisory control.

High-Tension Cables and Transmission Lines.

Apart from two failures, one of which was due to a pick, the 20 000-volt cables feeding the Wadi Bandar and Kurla substations have been free from trouble, and there have been no failures of the cables in the tunnels between Karjat and Thakurvadi on the Bhore Ghat.

The flashing-over of suspension insulators on the 100 000-volt lines has already been mentioned; with this exception these lines have been entirely free from trouble. The flashing-over, though annoying, is not a serious matter, as in all cases the high-tension feeder switch is reclosed immediately. From the beginning of March 1931 to the end of November there were only 16 occasions on which the switches opened, 10 at the line-sectioning point at Karjat, and 6 at the power station; whereas in January and February the total number was 27. Galvanized-steel plates have now been fitted to the cross arms immediately above the insulator strings, and in consequence the number of flash-overs has been greatly reduced. Thus in December 1931 the high-tension feeder switches were brought out on 4 occasions only, as compared with 15 in December 1930.

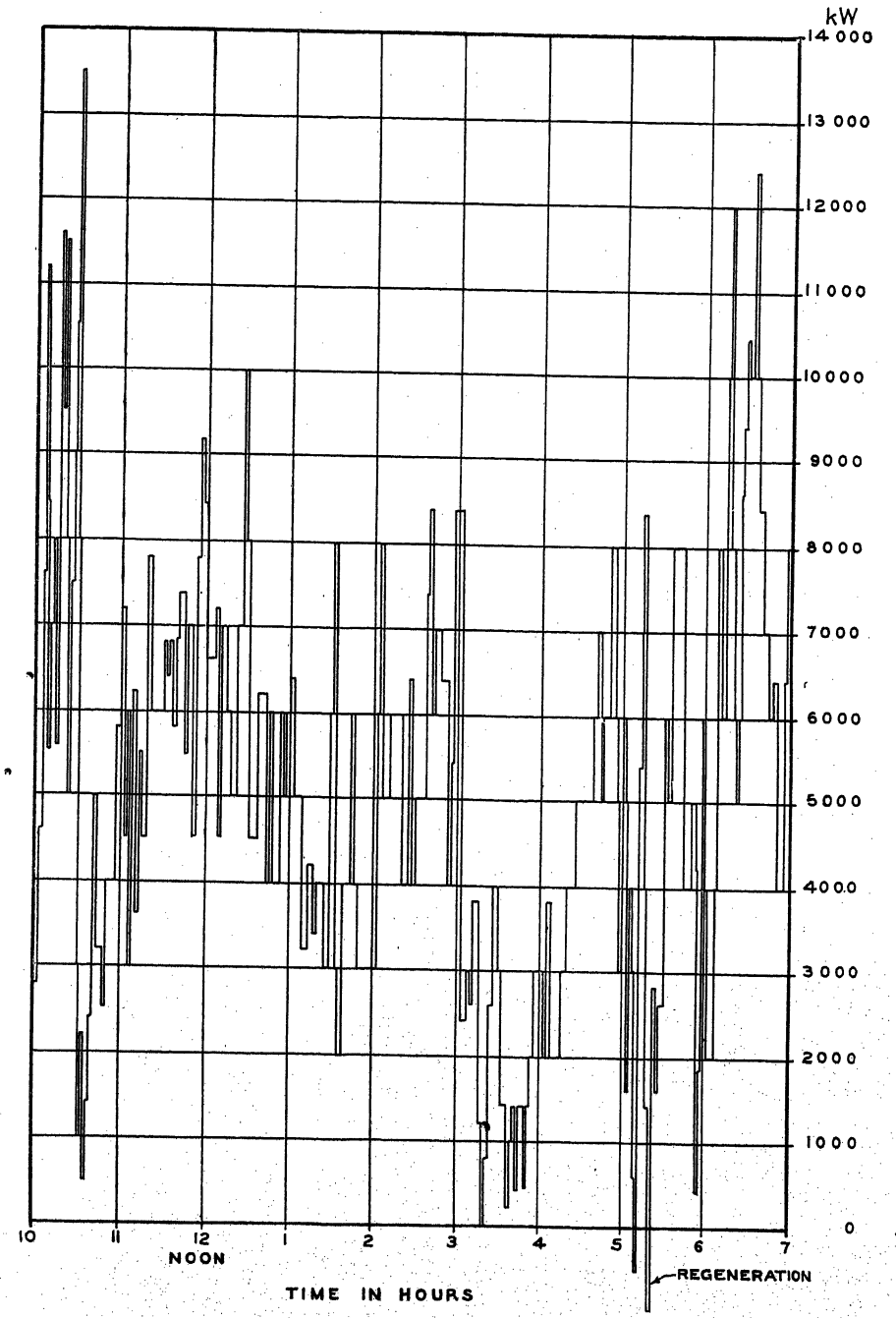


FIG. 26.—Load chart of Kalyan power station.

Power Station.

There is little to be said of the operation of the power station. It went into service with less than the usual

number of minor disturbances incidental to the starting-up of plant of this magnitude, and has been free from serious trouble ever since. The output being substantially below the forecast for which the station was designed, the operating efficiency is slightly less than the estimated figure.

The principal feature of interest is the excellent result obtained from the supplementary oil-firing of the boilers. The fluctuations of the load, of which a sample is given in Fig. 26, are, as anticipated, sudden and considerable, but have given rise to no difficulty as the overload output of the boilers is obtainable almost at a moment's notice. The flexibility of operation is remarkable and, what is specially important, is obtained at very small cost. The price of oil fuel is naturally higher than the price of small coal, even allowing for the difference in calorific value. It is, therefore, essential that the quantity of oil used should be kept down as much as possible. The following figures for 6 successive weeks show that this has been successfully accomplished:—

Consumption of coal, tons . 780, 747, 774, 749, 782, 776 (9 800 B.Th.U.)
Consumption of oil, tons ..2·8, 2·0, 4·0, 1·0, 2·0, 3·2 (18 800 B.Th.U.)

No trouble of any kind has been experienced with the circulating-water intake, due either to silt in the river or to obstructions, and it is only necessary to run the screens about an hour a day.

As will be seen from the load chart in Fig. 26, the return of regenerated power to the power station is not infrequent. The surplus power is usually absorbed by the station auxiliaries, but if the input is substantially in excess of the auxiliary load the generators begin to speed up. Before they reach the limit set by the emergency governor, a frequency relay at Karjat closes and a tank resistance capable of absorbing 1 500 kW is connected to the overhead line. On one occasion the frequency relay failed to act, without, however, any serious results, the power-station staff opening the feeder circuit breakers before the rise in speed became excessive.

Responsibility for Design and Construction.

In the initiation and carrying out of this electrification scheme the successive Agents of the Railway have naturally taken a very important part. In the earliest stages after 1918 this position was occupied by Sir Lawless Hepper, but before matters had proceeded very far he retired, and Mr. Rumbold and then Mr. Hawes succeeded him as Acting Agents. In April 1922 Sir R. McLean was appointed and carried through the final discussions with the Government of Bombay and the Railway Board, having already, in his position as Deputy Agent, been in close touch with the matter. During his term of office, until he retired early in 1927, he was responsible for all arrangements and negotiations in connection with the construction and setting to work of the suburban scheme and for the preparation and presentation to the Railway Board of the case for the main-line scheme. On his retirement he was succeeded by Mr. T. Guthrie Russell, and, on the latter's appointment in the middle of 1928 to the Railway Board as Chief Commissioner of Railways, by Mr. D. S. Burn. Last December Mr. Burn retired and was succeeded by the present Agent, Mr. A. E. Tylden-Pattenson.

All construction work in India has been under the general supervision of the Chief Engineer of the Railway, Mr. R. V. Symons, until 1928, and Mr. E. Fraser from 1928 to 1930. The Chief Transportation Superintendent has been responsible for operation, through his Deputy (Electrical) Mr. F. L. Otter, specially appointed for this purpose.

The consulting engineers, Messrs. Merz and McLellan until September 1927, and Messrs. Merz and Partners thereafter, were responsible for the design of both the suburban and main-line schemes, for advising the Railway Company and subsequently the High Commissioner as to the placing of the various contracts, except those let to contractors in India, and for the supervision, erection, and setting to work. The India Stores Department, under the Director, Sir Stanley Padden, was responsible for the administration of the contracts placed in this country. The consulting engineers' chief representative in India was Mr. G. B. Gill until June 1925, and from then until the end of last year Mr. G. E. F. Webber. The site works at the power station, and the screen and pump house, were to the designs of Messrs. Rendel, Palmer and Tritton, in collaboration with Messrs. Merz and McLellan. All civil engineering work, including buildings (apart from the steel framework of the power station) and track structure foundations, was carried out by Indian contractors under the direction of the Chief Engineer, and in particular Mr. R. Sephton of the Chief Engineer's Department.

Acknowledgments.

The author wishes gratefully to acknowledge his indebtedness to the G.I.P. Railway and its officers for much of the information contained in this paper, also to Mr. G. B. Gill and Mr. G. E. F. Webber for assistance in its preparation, and Mr. H. E. Gaze, who has been responsible for the drawings from which the illustrations have been produced.

APPENDIX.—PARTICULARS OF PLANT AND NAMES OF CONTRACTORS.

Multiple-Unit Trains.

Contractors:—

Electrical equipments (53) ..	English Electric Co., Ltd.
Coach bodies (52; 12 ft.) ..	Cammell Laird and Co.
Coach bodies (25; 10 ft.) ..	Cammell Laird and Co.
Coach bodies (15; 10 ft.) ..	Eisenbahn Liefergemeinschaft
Bogies (154)	Cammell Laird and Co.
Bogies (30)	Société Franco-Belge de Matériel de Chemins de fer

Technical Particulars:—

	12-ft. stock	10-ft. stock
Tare weight of motor-coach ..	70·1 tons	62 tons (average)
Tare weight of 4-coach unit ..	196 tons	169 tons (average)

Seating capacity 4-coach unit	441	361
Length of coach over buffers	70 ft. 6 in.	71 ft. 7 in.
Composition of train unit	One motor-coach and 3 trailers	
Total weight of electrical equipment	51 150 lb.	
Weight of equipment on each bogie	17 200 lb.	
Distance between bogie centres	48 ft.	
Length of bogie wheelbase	10 ft.	
Number of motors per motor-coach	4	
One-hour rating of motor	275 h.p.	
Continuous rating of motor	250 amps. at 700 volts	
Ventilation of motor	Fan on armature	
Gear ratio	75/21	
Degree of reduction of motor excitation	40 per cent	
Dia. of driving wheels	43 in.	
Voltage ratio, capacity, and speed of motor-generator	1 400/120 V.; 5·5 kW; 2 200 r.p.m.	
Number of control steps—		
Resistance notches, series	5	
Running notches, series	2	
Resistance notches, parallel	4	
Running notches, parallel	2	
Type of vacuum exhauster	Reavell rotary, 164 cub. ft. per min.	
Maximum safe speed	65 m.p.h.	
Maximum speed in ordinary service	55 m.p.h.	
Average distance between stations	1·45 miles	
Maximum gradient	1 in 35	
Method of operating pantographs	Vacuum	
Working range of pantographs	5 ft. 3 in.	

Freight Locomotives.

Contractors	Metropolitan-Vickers Co.
Sub-Contractors for Mechanical Parts	Vulcan Foundry for 31 locomotives Swiss Locomotive Co. for 10 locomotives

Technical Particulars:—

Number of locomotives	41
Total weight of each locomotive	123 tons
Weight per axle	20·5 tons
Weight of mechanical parts	73·5 tons
Weight of electrical equipment	49·5 tons
Length over buffers	66 ft. 1 in.
Length between bogie pivots	30 ft. 0 in.
Fixed wheelbase	15 ft. 1 in.
Overall width	10 ft. 0 in.
Height over locked-down pantographs	14 ft. 6 in.
Motor equipment	Four motors
Wheel diameter and gear ratio	48 in.; 33/137
Number of motors per locomotive	4
One-hour rating of motor	650 h.p.
Continuous rating of motor	310 amps. at 1 400 volts
Method of ventilation	External blower and fan on armature
Number of blowers	Four
Number of motor-generators	One
Voltage and capacity of motor-generator set	1 400-volt motor; 2-kW 50-volt generator
Continuous rating of each axle-driven generator for excitation	310 amps., 37 volts, 500 r.p.m.
Weight of active material in main resistances	7 087 lb.
Type of main resistance	Cast iron
Number of steps of controller:—	
Resistance notches, series	16
Running notches, series	3
Resistance notches, series-parallel	15
Running notches, series-parallel	3
Resistance notches, parallel	15
Running notches, parallel	3
Maximum degree of reduction of motor excitation	39·5 per cent in two steps
Number of excitation notches for regeneration	15 in each motor combination
Number of main contactors, including line switches	48
Cam-operated switch groups and reversers	8
Method of operating main contactors	Electro-pneumatic
Tractive effort on first notch of controller	9 200 lb.
Type of fuse for auxiliary circuits	Expulsion and cartridge
Auxiliary battery	Chloride
Number of cells, and capacity	24; 90 ampere-hours
Method of operating pantographs	Compressed air
Maximum range of pantographs	8 ft. 0 in.
Working range of pantographs	6 ft. 2 in.
Number of contact strips per pantograph	16
Normal pressure of each pantograph on contact wire	24 lb.
Number, type, and capacity of exhauster	Two, rotary; 244 cub. ft. per min.
Type and capacity of compressor	Reciprocating; 38 cub. ft. per min.
General arrangement of locomotive	See Fig. 5
Performance curves of motors	See Fig. 6

PASSENGER LOCOMOTIVES.

	M.V. locomotive	Brown-Boveri locomotive	G.E.C. locomotive
Contractors	Metropolitan-Vickers Co.	Brown-Boveri Co.	General Electric Co.
Sub-Contractors for Mechanical Parts	Swiss Locomotive Co.	Hawthorne, Leslie and Co.	Hawthorne, Leslie and Co.
Technical Particulars:—			
Number of locomotives ..	22	One	One
Total weight of each locomotive	103 tons	111 tons	114 tons
Weight per driving axle ..	21 tons	19·2 tons	20·7 tons
Weight of mechanical parts ..	65·5 tons	66 tons	69·5 tons
Weight of electrical equipment	37·5 tons	45 tons	44·5 tons
Height of centre of gravity ..	6 ft. 1½ in.	6 ft. 1 in.	5 ft. 6½ in.
Length over buffers	53 ft. 6 in.	56 ft. 2 in.	56 ft. 2 in.
Overall width	10 ft. 0 in.	10 ft. 0 in.	10 ft. 0 in.
Height over locked-down pantographs	14 ft. 4 in.	14 ft. 4 in.	14 ft. 6 in.
Motor equipment	6 motors	6 motors	6 motors
Wheel diameter and gear ratio..	63 in.; 32/58 1st train 48/97 2nd train = 1:3·66	69 in.; 38/123 = 1:3·24	74 in.; 23/86 = 1:3·74
One-hour rating of motor ..	360 h.p.	370 h.p.	375 h.p.
Continuous rating of motor ..	355 amps. at 700 volts	360 amps. at 700 volts	425 amps. at 700 volts
Method of ventilation	External blower and fan on armature	External blower and fan on armature	External blower and fan on armature
Number of blowers	Two	Two	Two
Number of motor-generators ..	One	One	One
Voltage and capacity of motor-generator set	1 400-volt motor; 2-kW 50-volt generator	1 400-volt motor; 1·8-kW 50-volt generator	1 400-volt motor; 2-kW 50-volt generator
Weight of active material in main resistances	10 370 lb.	6 500 lb.	3 900 lb.
Type of main resistances ..	Cast iron	Cast iron	Cast iron
Number of steps of control:—			
Resistance notches, series ..	15	12	12
Running notches, series ..	3	3	3
Resistance notches, series-parallel	14	12	9
Running notches, series-parallel	3	3	3
Resistance notches, parallel..	14	12	9
Running notches, parallel ..	3	3	3
Maximum degree of reduction of motor excitation	44 per cent in two steps	35 per cent in two steps	30 per cent in two steps
Method of reduction of excitation	Field tapping	Field tapping and shunting	Field shunting
Number of main contactors, including line switches	23	34, cam-operated	48
Cam-operated switch groups and reversers	7	2	1
Method of operating main contactors	Electro-pneumatic	Cam shaft	Electro-pneumatic
Tractive effort on first notch of controller	7 500 lb.	8 300 lb.	8 200 lb.
Type of fuse for auxiliary circuits	Expulsion and cartridge	Expulsion and cartridge	Expulsion and cartridge
Auxiliary battery	Chloride	Storage Battery Co.	Chloride
Number of cells, and capacity..	24; 90 amp.-hour	24; 100 amp.-hour	24; 90 amp.-hour
Method of operating pantographs	Compressed air	Compressed air	Compressed air
Maximum range of pantographs	8 ft. 0 in.	7 ft. 7 in.	7 ft. 0 in.
Working range of pantographs	6 ft. 2 in.	6 ft. 7 in.	6 ft. 2 in.
Number of contact strips per pantograph	16	12	14
Normal pressure of each pantograph on contact wire	24 lb.	24 lb.	24 lb.
Number, type, and capacity of exhausters	Two; rotary; 242 cub. ft. per min.	Two; rotary; 234 cub. ft. per min.	Two; rotary; 242 cub. ft. per min.
Type and capacity of compressor	Reciprocating; 38 cub. ft. per min.	Reciprocating; 26 cub. ft. per min.	Reciprocating; 38 cub. ft. per min.
General arrangement of locomotive	See Fig. 9	See Fig. 10	See Fig. 8
Performance curves of motors..	See Fig. 7	—	—

TRACK EQUIPMENT.

Contractors:—

Overhead-line equipment	British Insulated Cables Co.
Bonds	Établissements Metallurgiques de Rai-Tillières Messrs. Felten and Guilleaume British Insulated Cables Co.
Structure foundations	Mawson and Vernon Co. and Hindustan Construction Co. In suburban area by G.I.P. Railway

Technical particulars	Sections outside suburban area	In suburban area
Total single-track mileage (sidings and running lines)	447 miles	124 miles
Normal height of contact wire	18 ft. 10 in.	16 ft. 6 in. up to Thana; 18 ft. 6 in. beyond
Maximum and minimum height of contact wire	20 ft. 6 in. and 14 ft. 10 in.	19 ft. and 14 ft. 10 in.
Normal sag of catenary	6 ft. 0 in.	6 ft. 0 in.
Spacing of supporting structures	220 ft.	220 ft.
Spacing of droppers to auxiliary catenary	6 per span of 220 ft.	12 per span from catenary to contact wire
Spacing of droppers from auxiliary catenary	12 per span of 220 ft.	—
Curves for which one intermediate pull-off structure is required	Below 4 880 ft. radius	Below 4 880 ft. radius
Curves for which two intermediate pull-off structures are required	Below 1 210 ft. radius	Below 1 210 ft. radius
Sectional areas of wires:		
Contact wire	0·3 sq. in.	0·25 sq. in.
Auxiliary catenary cable	0·2 sq. in.	—
Catenary cable	0·5 sq. in.	0·375 sq. in.
Feeder cables	1·0 and 0·75 sq. in.	—
Material of insulator	Porcelain	Porcelain
Structures	Grey beam section planted in concrete	Fabricated and secured by bolts embedded in foundations
Catenary suspension	Two 7-in. suspension-type discs	Bracket and two 7-in. suspension-type discs
Terminal strain insulators	Shackle type	Shackle type
Cross-span registration	Disc and loop type	Bracket insulator with steady-arm and disc and loop-type insulators
Number and section of bonds per 100-lb. rail joint	2 × 0·153 sq. in. section	2 × 0·153 sq. in. section

SUBSTATIONS.

(A) *Bombay to Kalyan.*

Contractors:—

Equipments (8)	Metropolitan-Vickers Co.
(6)	English Electric Co.
Switchgear	Ferguson Pailin, Ltd. Reyrolle and Co.

Technical Particulars:—

Number of substations	4 (2–4 unit and 2–3 unit)
Method of control	All attended
Number of rotary sets	14
Number of machines per set	2
Capacity of each rotary set, continuous rating	2 500 kW
Overload capacity of each rotary set	3 000 kW for 2 hours
Speed of rotaries	600 r.p.m.
Phase voltage on a.c. side	550 volts
Ventilation of rotary	Fan on armature
Method of protection against overloads	High-speed circuit breakers
Method of starting	Starting motor
Number of track section cabins	5
Number of breakers in track section cabins	34
Method of control of breakers in track section cabins	Breakers in the cabins operated by a.c. motors controlled from adjacent stations or signal cabins

(B) *Main Lines beyond Kalyan.*

Contractors:—

Plant, switchgear, and cabling	British Thomson-Houston Co.
Steel-frame buildings	Richardson and Cruddas, Ltd.

Sub-Contractors:—	
Steelwork for outdoor step-down substation	Heenan and Froude, Ltd.
Step-down transformers ..	British Electric Transformer Co.
22 000-volt switchgear.. ..	Reyrolle and Co.
Supervisory control gear ..	Standard Telephones and Cables, Ltd.
Technical Particulars:—	
Number of substations ..	11 (4 triple-unit, 7 double-unit)
Method of control	5 attended, 6 unattended
Number of rotary sets ..	26
Number of machines per set ..	2
Capacity of each rotary set (continuous rating)	2 500 kW
Overload capacity of rotaries..	4 375 kW for 1 hour; 7 500 kW for 5 minutes
Speed of rotaries	600 r.p.m.
Phase volts on a.c. side ..	560 volts
Method of protection of rotaries against overloads	High-speed feeder circuit-breakers; machine breakers operating on reverse power, and thermal relay for sustained overloads
Method of starting	Starting motor
Type of track-feeder breaker ..	High-speed truck type
Rotary temperature relay ..	Relay set to give warning at control point of any high temperature which, if persisted in, will open the breakers on the rotary set on d.c. side and when machines are cool again will permit them to be reconnected to the busbars
Capacity of fan on rotary armature	13 500 cub. ft. per min.
Number of track-sectioning cabins	11
Number of breakers in track-sectioning cabins	4 in each cabin
	Each breaker is closed by energizing the feeder it controls from the adjacent substation, its operating coil being connected to that feeder. The circuit breakers are opened by switching off all track feeders to the sectioning cabin, but in some cabins provision is also made for opening circuit breakers by supervisory control

Transmission System.

(A) 110 000-*Volt Lines.*

Contractors	Henleys Telegraph Works Co., Ltd.
Sub-Contractors:—	
Towers	Milliken Bros., Ltd.
Insulators	Bullers, Ltd.
Aluminium conductors ..	British Aluminium Co.
Steel wire	Richard Johnson and Nephew, Ltd.
Technical Particulars:—	
Type of line	Single circuit (except about 5 miles of line)
Voltage	110 000 volts
System of suspension	Triangular
Conductors per line	Three (except on double-circuit line)
Size of aluminium steel-cored conductor	0·1 sq. in. copper equivalent
Number and size of wires in conductor	Six 0·186 in. aluminium. Seven 0·062 in. steel
Number of earth wires ..	One
Number and size of discs per suspension string	7; 10 in. dia.
Number and size of discs per tension string	8; 10 in. dia.
Height and weight of suspension towers	68 ft. 9 in.; 4 200 lb.
Height and weight of angle towers	68 ft. 9 in.; 5 040 lb.
Height and weight of anchor towers	63 ft. 5 in.; 5 200 lb.
Total length of single-circuit line	272 miles
Type of road, railway, and telegraph line crossings	Each conductor made off on twin sets of strain insulators

(B) *Cables.*

Contractors:—	
For suburban section	Callenders Cable Co.
For main-line section	British Insulated Cables
Technical particulars:—	
Working voltage between phases	22 000 volts
Type of cable	Paper-insulated lead-sheathed, and wire-armoured
Depth laid in ground	36 in.
Protection in the ground ..	Reinforced-concrete covers
Length of size and power cables:—	
Suburban	18·5 miles; 0·15 sq. in.
	5·5 miles; 0·2 sq. in.
Main line	3·6 miles; 0·15 sq. in.
Length and number of cores of pilot cable	8 miles; 9 cores

Power Station.

Contractors:—	
Power station foundations ..	Hindustan Construction Co.
Pump-house building	Mawson and Vernon
Steel-frame buildings	Babcock and Wilcox

Boiler-house equipment and pipe work	Babcock and Wilcox
Coal and ash plant	Babcock and Wilcox
Oil-firing equipment	Babcock and Wilcox
Turbo-alternators and condensers	C. A. Parsons and Co.
Switchgear and cabling ..	English Electric Co.
Outdoor substation steelwork..	Heenan and Froude
Unit and step-up transformers	Metropolitan-Vickers Co.
Pump-house equipment ..	Mirrlees Watson and Co.
Circulating-water screens ..	Brackett and Co.
6 600-volt and 415-volt unit switchgear	Reyrolle and Co.
110-volt battery	Chloride Co.
Evaporating plant	Babcock and Wilcox (*Sub-Contractor G. and J. Weir*)

Technical Particulars:—

Number of boilers	6
Normal capacity (coal-firing) ..	60 000 lb. per hour
Overload capacity (coal plus oil-firing)	105 000 lb. per hour
Working pressure	270 lb. per sq. in.
Temperature of superheated steam	725° F.
Forced-draught motors ..	50 h.p.
Induced-draught motors ..	145 h.p.
Forced-draught motor for oil-firing	5 h.p.
Temperature of flue gases ..	315° F.
Temperature of feed water ..	130° F.
Boiler efficiency with coal firing	86 per cent
Oil-fuel tank capacity (two tanks 30 ft. 0 in. dia., 12 ft. 0 in. high)	400 tons total capacity
Oil service tank capacity ..	15 tons each
Stokers	Two per boiler; B. and W. chain grate, compartment type 8 ft. 6 in. × 18 ft. 0 in.
Span and capacity of engine-room crane	72 ft. 0 in.; 60 tons
Number of turbo-alternators..	4
Rated capacity per turbo-alternator	10 000 kW (max. cont. rating) 3-phase at 0·9 power factor (lagging)
Frequency, speed, and voltage	50 cycles; 3 000 r.p.m.; 6 600/6 750 volts
Two minutes' overload capacity	16 500 kW at 0·9 power factor
Type of turbine	Single-cylinder reaction-type single condenser
Steam consumption on full load	10·0 lb. per kWh
Condenser surface	14 500 sq. ft.
Number and capacity of circulating-water pumps	Three of 16 000 gallons per minute against 47 ft. head Two of 8 000 gallons per minute against 47 ft. head
Type and capacity of coal-handling plant	Four belt conveyors, each 100 tons per hour
Type and capacity of ash-handling plant	Submerged paddle wheel and belt conveyors, each 6 tons per hour
Number, capacity, and voltage ratio of unit transformers	5; 1 800-kVA; 6 600/415 volts
Rated capacity of 6 600-volt circuit breakers	3 000 amperes
Number and capacity of step-up transformers	4; 11 000 kVA
Type of transformers	Single-phase oil-immersed self-cooled
Guaranteed full-load efficiency of step-up transformers	98·93 per cent
Number and type of lightning arrestors	4; oxide film
Number of evaporators ..	Two triple-effect units
Output of distilled water from each evaporator	10 000 lb. per hour
Steam consumption of each evaporator	4 300 lb. per hour

Discussion at a Joint Meeting of The Institution and the Institute of Transport, 28th April, 1932.

Mr. F. Pick: I understand that the scheme which has been put into force on the G.I.P. Railway was originally designed to deal only with the suburban traffic of Bombay. Once the company had begun to electrify their system they soon found that the grades encountered on the Ghats and the problem of tunnel ventilation could best be dealt with by extending their electrification scheme. In England the Southern Railway had a similar experience; they started by electrifying their suburban lines round London, and are now engaged in electrifying the route to Brighton. It seems strange to me, as a layman, that there should be so many types of electrification schemes each with its own voltage and kind of current. The electrical engineer is always an enthusiast for electrification, but when he tries to convert his lay principals or lay colleagues, his troubles begin. He cannot show them that he is right in his conclusions as to the most suitable type of electrification to adopt. Perhaps, coming from the Institute of Transport to the Institution of Electrical Engineers, I might utter that one word of warning. Electrical engineers and transport experts will have to get together soon to solve the problems of railway electrification, and I therefore welcome a discussion of the subject beforehand at a joint meeting of our societies.

Lieut.-Col. F. A. Cortez Leigh: The fact that both the main lines from Kalyan have to climb over the Ghats, whilst leading to an extremely interesting scheme from

an engineering point of view, at the same time makes it difficult to compare the valuable information given in the paper with the conditions which would apply if lines of the same length and traffic density were electrified in Great Britain. The author puts forward the claim that the adoption of coupled axles for the freight locomotives reduces the tendency to slip, and I should be glad if he would confirm that the weight per driving axle was limited to 20 tons for these as it was for the passenger locomotives. Could he state the limits of adhesion for the two types under similar conditions? A comparison between the drawings illustrating the general arrangements of the freight and passenger locomotives shows that some of the advantages claimed on page 919 as applying to the design including coupled axles can equally be applied to a locomotive without this feature, e.g. in both designs the driving motors may be carried on the trucks and spring-borne and arranged with a high centre of gravity, the motors being well above the driving axles. In addition the electrical equipment, if not so easily divisible into two groups, can be, and on the passenger locomotives has been, subdivided into groups. Apart, therefore, from the improved performance claimed as regards adhesion, the main advantage of the design chosen for the freight locomotives of this capacity consists in the low-speed performance which is possible with four 1 500-volt motors in series instead of six 750-volt motors. The information given in regard to the tractive resistance of the passenger locomotives is very valuable, and in view of the discrepancies which exist in regard to the track resistance of locomotive-hauled trains it would be appreciated if the author could submit a curve relating the tractive resistance on the level with speed, both in calm weather and under head-wind conditions. With regard to the design of the overhead equipment, it is not very clear why the double contact-wire system (*a*) required more maintenance than the single-wire system, and (*b*) lost after a time its initial advantage from the point of view of current collection. Further information as to the nature and extent of the maintenance work on the contact wire would be appreciated, and in particular I should like to ask whether any corrosive effects have been noticed due to the atmosphere, which is believed to be salt-laden. What is the amount and rate of wear of the contact wire and of the pantograph strips in terms of pantograph passages? The author's description of the bonding of the structures to the rails is interesting, but no mention is made of the maximum potential of the return rail; information as to the value of this on the suburban and main-line sections respectively would be appreciated. What type of material was used for the insulation between the base of the structure and the concrete plinth, and for insulating the foundation bolts and nuts from the structure? I should be interested to know the value of the current which was found to be sufficient to disintegrate the concrete before these precautions were adopted. Turning to the section dealing with capital expenditure, according to Fig. 12 the single-track mileage of the main-line section alone is 333 miles, and from page 935 it would therefore appear that the cost of permanent-way equipment per single-track mile (£4 700 on this basis) is relatively high, whereas the cost of the alterations to ways and works (at £146 per single-track mile) is extraordinarily low. This suggests, as is indicated elsewhere in the paper, that no great difficulty was experienced in siting the structures. The value of the schedule of costs on page 935 would also be increased if the author would state the price of copper when the contract was placed. The average cost of each sub-station (£68 000) appears to be high. What arrangements were made for dealing with the steam locomotives displaced by this electrification? Has it been possible to absorb them in the remainder of the system, and what value was given to this item in the investigation which decided in favour of electrification of these lines? With regard to operation and maintenance costs, it would be interesting if the author would subdivide Items 5 and 6 in the schedule given on page 938 between suburban and main-line substations, and also if he would distinguish between manual- and remote-control main-line sub-stations. With regard to the overhead equipment, the maintenance charges on this work include 272 miles of single-circuit 110 000-volt transmission line, and it is therefore impossible to allocate what is due in respect of track equipment alone. It would be of considerable interest if this figure could be made available.

Sir Clement Hindley: The G.I.P. Railway is owned by the Government of India, and although up to 1925 it was managed by a company, the capital required for the electrification scheme was provided by the Government. I was fortunate enough to be the principal railway adviser to the Government when the decision was taken to undertake the electrification of the main-line portion of the railway. The decision to spend 5½ to 6 million pounds on an electrification scheme required a good deal of courage, but the Government was fortunate in having good financial advice, as I had as my colleague on the Railway Board the late Mr. George Sim, to whose financial genius the Indian railways owe much. We were assisted by receiving from the author's firm a scheme prepared in great detail and fortified by very complete estimates. I question the statement (page 911) that the G.I.P. electrification system has no equal in magnitude in the British Empire with the exception of the Southern Railway scheme. In my opinion the Southern Railway system is not an exception because it is not a main-line electrification scheme; it is merely an extension of a suburban electrification. The G.I.P. Railway main-line electrification is the only one of its kind in the British Empire, and in view of its size —over 500 track-miles—it is a very important scheme. Regarding the scheme as a development of transport, I have a record of a journey from Bombay to Poona undertaken in 1804 by Lord Valentia which took 6 days. He travelled by palanquin, 40 porters being engaged to carry the palanquins of himself and his two friends in relays. In 1830 Sir John Malcolm built the first road over the Ghats, and the journey was reduced to one of 24 hours by horse carriage. In 1863 a railway was built over the Ghats, and the time taken for the journey was reduced to 6 hours. During the next 30 or 40 years the time was reduced to something under 4 hours by improved steam traction. At the present time the fastest electric mail train does the journey in 2¾ hours. I should like to draw attention to the large size of the coaches adopted on the Bombay suburban railway; they are 12 ft. wide and each

is capable of a crush loading of 200 people. A 2-unit train will therefore carry 1 300 to 1 400 people. The problem of getting such a number of people out of the station before the next train comes in is sometimes a difficult one. The solution to the problem of providing an efficient transport system between Bombay and Poona is to some extent due to the important civil engineering work of realigning the Bhore Ghat section of the railway. This involved some heavy tunnelling and resulted in the elimination of a reversing station. The Ghats consist of a great escarpment which runs north and south down the west coast of India, and, owing to their position, the watershed between the east and west coasts in the neighbourhood of Bombay is only 40 miles from the latter. From the top of the Ghat section the plateaux and plains of India stretch away 1 200 or 1 500 miles to the east. Drainage proceeds from the top of this escarpment down to the mouth of the Ganges in Calcutta, and the rivers in Southern India. In the old days trade and commerce naturally followed the water, and Bombay was therefore largely cut off from trade with the rest of India for a long time after it came into our possession in the reign of Charles II. It was the urge to get into touch with trade in Central India that led our ancestors to make these successive improvements in the means of transport over the Ghats. Some figures to which I have recently had access show that although the traffic on the electrified sections of the G.I.P. Railway has not yet reached the expected figure, the return on the capital expended is satisfactory. The author points out that, as regards the passenger traffic, the train-miles for the year September 1930 to August 1931 were in the neighbourhood of 1 600 000, compared with the forecast of 1 953 000 for the fifth year after opening, while the goods ton-mileage for the year 1931, owing to exceptionally bad trade conditions, was some 30 per cent below that for 1921. On the other hand, I am informed that on the full capital expenditure of some 5 millions sterling the return due to savings in working expenses can be shown to be 6½ per cent if full credit is taken for the steam locomotives and oil and coal waggons released for use elsewhere. If credit is only taken for half these vehicles the return on capital is 5 per cent, and if no credit is taken the return is 4·1 per cent.

Lieut.-Col. H. E. O'Brien: With regard to Mr. Pick's remark about the number of types of electrification schemes available, I understand that in this country a standard system has been definitely settled upon for use when the time comes for main-line electrification. Although it is interesting to find that the results obtained on the G.I.P. electrification scheme have turned out so closely as expected, it is obviously rather early yet to say that the full measure of maintenance charges has been met. It is to be hoped we shall be given a second paper in the course of two or three years which will amplify the results indicated in this paper, and will enable us to judge whether the present 6½ per cent return on the capital will be increased or diminished. In connection with the design of the locomotives, the number of armature failures on multiple-unit trains is rather surprising. It would be interesting if, in the course of the discussion, speakers who have had large numbers of d.c. motors under their charge would give comparative figures of armature and motor failures, as on some systems motor failures are practically non-existent. The gear failures are also of interest: on the Bombay and Baroda Railway an absolutely satisfactory gear has apparently been evolved, and it would therefore be of interest to know whether the failures on the G.I.P. Railway were due to the administration having accepted the lowest tender, or whether they were incidental to one of those experiments which are essential to progress. In my opinion the slipping of the locomotives was due to the use of laminated springs on the individual drive; there is a hysteresis effect in connection with laminated springs which tends to cause the weights to shift from wheel to wheel, and gives rise to a tendency to slip which is not so liable to occur if helical springs are employed. On the other hand, helical springs are liable to cause rocking of the locomotive if the track is bad, and this may render necessary some form of damping. The author's statements about the track mileages are not very clear; I should be glad if he could state how much of the mileage is made up of main line, how much of sidings, and how much of suburban line. It would also be interesting to have a more explicit comparison between the costs of steam-locomotive and electric operation. It is a remarkable feat to have replaced 171 steam locomotives by 65 electric locomotives. In view of the fact that the annual mileages are of the order of 60 000 for passenger and 24 000 for freight locomotives, however, I should like to know whether the difficulties that were encountered in the schemes prepared in connection with the Weir Committee's Reports in finding suitable workings for the locomotives are not also encountered in the G.I.P. Railway electrification. In Switzerland the freight locomotives appear to cover much larger annual mileages than are achieved in India. It would be interesting to know whether the two trial locomotives which were prevented from taking part in the main contract are running, and whether they are giving good results. In considering what the results of main-line electrification are likely to be, we have to devise ways of reducing the cost per engine-mile by achieving large reductions in the cost of repairs. Assuming that the anna is worth 1d., the cost of repairs to passenger locomotives appears to be a little under 1¼d. per mile. I presume that the author's figure of £212 for the repairs per passenger locomotive does not include overhead charges, i.e. that the work was done by direct labour. This figure is equivalent to about ⅓d. per mile, and by adding general charges and allowances for other contingencies we arrive at a figure of about 1½d. per mile. The repairs cost of one of the large Continental a.c. electrifications was of the order of 2d. to 2⅓d. per mile. The fact that the shed charges given in the paper are higher than the cost of repairs suggests that the inspection may have been rather overdone through anxiety to secure an absolutely satisfactory result. A hint to this effect was given in the paper* by Messrs. Merz and Lydall at the World Power Conference in Berlin in 1930. In the present state of electric locomotive design we ought to be able to produce locomotives capable of running for very long periods practically without inspection. A little

* C. H. Merz and F. Lydall: "The Economical Operation of Electrified Railways," *Transactions of the Second World Power Conference*, 1930, vol. 17, p. 234.

more explanation about the cost of the shed repairs would therefore be welcome. With regard to the question of the train crew, whereas the cost of repairs has been brought down from about 6d. to 2d. or 3d. per mile, the expenditure on train crews remains practically the same as it was with steam working. Although I have ridden a good deal on electric locomotives, I have never travelled on one where the second man had any duties to perform. I am surprised that to-day, when we have automatic signalling, the possibilities of constant telephonic communication between the driver and the guard, and of short-wave wireless communication between the driver and the signal box, route signalling, colour light signalling, train stops, dead man's handles, and many other safety devices, we are making no progress towards the one-man operation of locomotives. The Hungarian railways, which are carrying out extensive electrification—very largely with British locomotives—intend (it is stated) to adopt one-man operation of the locomotive. Reverting to the question of the return on capital, it should be noted that the real question for the railway company is whether the return of 6½ per cent on this capital could have been obtained by spending the money in any other way. It is quite clear that the only sums really chargeable to capital in a railway electrification scheme are those involved in the electrification of the track, plus the value of any increase in the total haulage capacity of the aggregate locomotive stock. It is a pity that more attention was not paid to reducing the train resistance on the express locomotives and the fast trains built specially for the Bombay-Poona service. The additional cost would have been small, and apart from the economy in current consumption some very interesting experimental work could have been accomplished. Railway companies contemplating electrification will note with some satisfaction that—as is evident from the results obtained here, in Natal, and elsewhere—the power consumption of an electrification scheme can be very accurately predicted.

Mr. H. W. H. Richards: It would be interesting to know the single-track running miles on the three main sections of line, and also the traffic densities (in trailing ton-miles) on those sections under the original steam conditions, since it is suggested that the single-track running mile forms a good standard on which to base operating particulars and costs. In view of the large amount of multiple-unit working and the necessity for simplicity and reliability, the decision to use the 1 500-volt system on the G.I.P. Railway electrification appears to be very sound. In years to come, when the question of cheap running will be highly important and locomotives will be required to go on working with the minimum amount of maintenance, the decision to adopt the 1 500-volt system, which can be used for both suburban and main-line work, will probably be appreciated more and more by those in charge. It would be interesting to know whether track maintenance has increased appreciably as a result of the use of 70-ton motor-coaches which run at 55 m.p.h. with four axle-borne motors. Regarding the passenger locomotive which has a load of 21 tons on each of the three driving wheels, with a maximum tractive effort of 36 000 lb., giving a coefficient of adhesion of 25·5 per cent, was sand used when this locomotive slipped at Victoria terminus? As regards the overhead equipment, it would be interesting to know whether the up and down tracks are normally paralleled on the positive side. The negative busbar is not earthed at the substations, apparently in order to avoid trouble from electrolytic action. In the case of a 1 500-volt short-circuit, is not such an arrangement likely to cause danger to people on the line? I notice that the overhead transmission line was kept 300 ft. from the railway line; was this done in order to prevent interference with railway communication circuits? Was any cabling of communication circuits found necessary at this distance? What are the daily and annual temperature ranges in the part of the country traversed by the electrified section? It is stated in the paper that no signals had to be altered due to the overhead-line equipment: can the conclusion be drawn that similar overhead structures in this country would cause no obscuration of signals? The energy consumption figures appear to be very satisfactory.

Mr. B. G. White: The Ghat sections are very similar to parts of Switzerland, but whereas the trains in Switzerland are propelled by energy derived from water power, the trains on the Ghats are operated from a steam generating-station at Kalyan. This raises the interesting point that the Ghat sections nearest to the hydro-electric supply are operated from the steam generating-station, whereas the suburban sections, which are more remote from the hydro-electric supply, are operated from this latter source. What were the reasons for erecting the steam station, which consumes coal carried many thousands of miles and, with circulating-water temperatures up to 95° F., cannot be very efficient? Turning to page 935, the use of the word "capital" here seems to me to be misleading, as schemes of this kind almost invariably draw on both capital and revenue. I suggest that "cost of works" would be a more suitable term. Whereas the costs are given in some detail for the main line, they are not available for the suburban sections except in the form of a lump sum. Do the main-line costs include revenue and capital expenditure, freight, customs duty, and departmental and general charges; also have (*a*) credits and (*b*) alterations to telegraphs and telephones been taken into account? If credits were allowed, they should have been shown separately. Those of us who are engaged in this branch of engineering should do all in our power to reduce the cost of equipment. For instance, £10 saved on a mile of overhead equipment would result in a saving of more than half a million pounds sterling over the 51 000 miles referred to in the Weir Report. Much might be gained by some relaxation of the standards hitherto adopted, and I think that we should follow Continental practice and ensure that the expenditure falls as the reliability of plant increases. A lead in this direction has already been given by the Electricity Commissioners and the Central Electricity Board through reductions in the factors of safety.

Mr. E. H. Croft: The atmospheric conditions throughout the area in which the electrified sections of the G.I.P. Railway are operating give rise to great changes in temperature and a high value of humidity. Both the express and the ordinary passenger locomotives utilize

electro-pneumatic control, and I should therefore like to know whether any difficulties have been experienced in connection with excessive water condensation in any of the control or brake parts, and whether it has been necessary to introduce any additional apparatus over and above that which is supplied normally to overcome this trouble. In connection with coupling-rod drives (page 919), the author states that "the dead weight per axle is kept down to the lowest possible figure." The coupling rods represent a very appreciable dead weight in themselves, and such balance weights and pins as are required in conjunction with them also represent dead weight. While this is not equal to the unsprung mass of a motor which is axle-hung, it would appear that it is definitely greater than that of the unsprung parts of a quill drive. It would be interesting if the author would state whether, with the type of drive indicated, this is the case. The necessity of coupled wheels where regeneration is adopted is well known, and I should like to know whether the author would have utilized the same type of coupling-rod drive had regeneration not been introduced. I consider that the maintenance cost of such drives is high. Although the author states that in the freight locomotives the trucks were not articulated, at the reading of a recent paper, by the late Mr. Twinberrow,* designs were shown which indicated that the trucks were articulated in a special manner, i.e. from a rotation point of view, but not from a longitudinal point of view. This I regard as an undesirable feature, and I believe that the author has stated that locomotives with this articulation eliminated have proved more successful than those with articulation. Can he give any further information on this point? The figures for the train resistance of passenger trains are interesting: has the author found that the train resistance drops after a period of continuous running? Three express passenger locomotives were supplied, and apparently these were all satisfactory. Two of these locomotives have a symmetrical wheel arrangement, and the third (that of the Swiss Locomotive Works) has an asymmetrical wheel arrangement. It would be interesting if the author could give some particulars of the travelling properties of these three locomotives at high speed. Regarding the multiple-unit coaches, the number of delays per thousand train-miles due to the electrical equipment seems to be high. Table 9 shows that on two occasions multiple-unit trains caused traction-supply failure, i.e. the fault was of such a character that the circuit breakers at the substation operated before the protective apparatus on the train. It would be interesting to know the most common cause of faults and the form of protection adopted on the trains.

Prof. J. K. Catterson-Smith (*communicated*): A striking feature of the G.I.P. Railway electrification scheme is that the large hydro-electric stations operated by the Tata Companies are utilized for motive power to the extent only of serving the section between Bombay and Kalyan. Beyond this point power is derived from the 50 000-kW thermal station at Kalyan, built for the purpose at a cost closely approximating to a million pounds sterling. Fuel for the station is brought by rail from remote sources at great cost. The coal mined at Kargali costs about 5s. 6d. per ton at the pit, but on account of handling its price has increased to about 18s. 9d. per ton by the time it reaches the power station. One can only suppose that had the Bombay hydro-electric stations been under State or railway control the total power requirements would have been met by them, thus avoiding one large item of capital expenditure. With regard to the troubles caused by birds, I understand that in one week the short-circuits occasioned by their activities caused the burning-out of a number of rotary-convertor armatures. As to the large "crush hour" capacity of the G.I.P. Railway vehicles, those who have seen the conditions under which the Indian passenger travels will agree that he wastes no space. At the same time it is to be hoped that something may be done to improve these conditions, which do not make for comfort or health. The converting equipment for the railway was ordered before the mercury-arc rectifier had proved its suitability for traction, but presumably future extensions will be operated by plant of this type. I understand that the G.I.P. Railway has gained a large amount of valuable experience of the floodlighting of railway yards, and I should be glad of some information on this point.

Mr. F. Lydall (*in reply*): Mr. Pick is surprised that there should be so many types of electrification schemes, each with its own voltage and kind of current. So far as this country is concerned, I think everyone will agree that for all practical purposes only one type of current need be considered, namely direct current. Further, the committee appointed in 1927 by the Minister of Transport recommended that the voltage should be either 600 or 1 500 volts, although with the approval of the Ministry 3 000 volts might be used in exceptional circumstances. Thus in this country there is a choice between only two alternatives, and for any particular project there should be no difficulty in deciding between them.

I will endeavour to meet Colonel Cortez Leigh's request for further particulars, so far as the information is available. With regard to the weight and adhesion of the driving axles of the freight and passenger locomotives, the weights are given in the Appendix and the general question of weight and adhesion is dealt with in the last paragraph of page 921. No precise figures are available for the exact limits of adhesion of the various locomotives. Freight locomotives are able to exert a tractive effort of something over 80 000 lb. on dry unsanded rails, corresponding to an adhesion coefficient of about 1 to $3\frac{1}{2}$. The best record for the passenger locomotives shows that these are able to exert a tractive effort of about 35 000 lb. on sanded rails without slipping. With a total weight on the drivers of 63 tons this corresponds to a coefficient of about 1 to 4. As it was impossible to state in the paper the tractive resistance of the passenger locomotives, I am unable to give a curve showing the variation of the tractive resistance on the level with speed under different weather conditions.

Replying to the questions relating to the track equipment, the double contact-wire system gives excellent results when both wires are in perfect adjustment both individually and relative to each other. Comparatively

* J. D. TWINBERROW: "The Mechanism of Electrical Locomotives," *Proceedings of the Institution of Mechanical Engineers*, 1932, vol. 122, p. 51.

close adjustment must be maintained to ensure sparkless collection, particularly in special work where two wires tend to complicate the wiring, and naturally the adjustment of two wires relative to each other involves more maintenance time than is required for one wire. As regards the subject of corrosion, the smaller fittings are of non-ferrous material. Where ferrous fittings are used they are protected in the main by hot galvanizing, and, to some extent, by sherardizing, "schooping," or other processes. The results are conflicting; some of the galvanizing is still standing up well after several years, while in other cases there has been intensive corrosion. Wherever practicable, e.g. when making replacements, the use of non-ferrous material has been extended. The average wear on the suburban lines after some $3\frac{1}{2}$ years' running is equivalent to 0·0256 in. reduction in the vertical diameter per 120 000 pantograph passes. This excellent result is also reflected in the mileage obtainable from the pantograph strips. The insulation used at first for certain structures on the suburban lines was impregnated fibre, and subsequently, when this was found too soft, bakelized canvas board was adopted. On the main lines the anchor structures were insulated with white fibre sheet coated on site with bituminous paint.

A few tests have been made from time to time on the potential difference between the track rails and earth. This naturally varies on different parts of the system, depending on the number of tracks, the traffic density, and the distance between substations. Probably the highest figures are to be expected on the Harbour branch, which has only two tracks, and where there is considerable traffic during the morning and evening rush hours. The distance between the substations at Wadi-Bandar and Kurla via the Harbour branch is 8 miles. Tests taken at Sewri, 5 miles from Kurla, showed that the average potential difference from rails to earth between 9.0 and 10.30 a.m. was 7·7 volts; at Gowari, $3\frac{1}{2}$ miles from Kurla, the average potential difference between 8.30 and 11.0 a.m. was 4·9 volts.

In regard to the cost of the track equipment, the main-line scheme includes 447 miles of single-track equipment, the particulars of which are given below. On this basis the cost per mile works out at much less than £4 700.

I am unable to give complete information as to the disposal of the steam locomotives displaced by electrification. A certain number of these locomotives have been transferred to other railways, but beyond that I have no information. The question of what value should be assigned to the displaced locomotives in the investigation on the basis of which electrification was sanctioned was never, so far as I am aware, finally settled. The estimates showed that the electrification scheme would be remunerative even if no credit were taken for the value of the displaced steam locomotives.

It is not practicable to separate the maintenance costs of the various types of substations or of the track equipment and the high-voltage transmission lines. The whole of this work is carried out by the distribution department, and the costs are not segregated.

Replying to Colonel O'Brien's question in regard to the track mileages, the respective figures for the main-line and suburban schemes are: main-line 447 miles, suburban 124 miles. These figures are given in the Appendix as revised for the *Journal*. Included in the 447 miles there are 293 miles of running track equipped with 1 sq. in. of copper, 46 miles of running track in the suburban area equipped with 0·625 sq. in. of copper (of which 36 miles had already been equipped with structures under the suburban contracts), and 108 miles of sidings. Included in the 124 miles of equipment for the suburban scheme are 29 miles of sidings.

The two sample locomotives supplied respectively by the General Electric Co. and Messrs. Brown, Boveri, and Co., are giving good results. They are run in just the same way as the 22 locomotives supplied by the Metropolitan-Vickers Co.

I have given above the information asked for by Mr. Richards in regard to the mileage of single-track running lines. It is not so easy to give particulars of the traffic densities on the various sections under steam conditions, as some of the lines have only been in use since electric operation started. For the main-line traffic, the gross ton-mileage of goods trains in the year 1922–23 was about two-thirds, and the passenger train-mileage about 85 per cent, of that given in Table 4.

In reply to Mr. Richards's question as to track maintenance, while there has been some increase in the wear of the rails at certain points since electric working started, taking the track as a whole the extra wear is not considerable in view of the increase in the ton-mileage of trains passing over the lines.

In the test mentioned in the paper, during which a single passenger locomotive hauled a load of 480 tons from Bombay to Kasara, sand was not used when slipping of the driving wheels occurred as the train started from Victoria terminus.

Throughout the electrified area the overhead lines for the up and down tracks are paralleled on the positive side both at the substations and at the track-sectioning cabins. There has been no indication that the arrangement of the negative busbars, which are connected to the track rails but are not earthed at the substations, is likely to cause danger to people on the line. The overhead transmission lines are separated by not less than 300 ft. from the railway line in order to guard against interference with the railway communication circuits; the scheme has been successful to the extent that it has not been found necessary to cable any of these circuits.

The daily and annual temperature ranges differ considerably from one part of the line to another. In and near Bombay the shade temperature is seldom more than 90° to 95° F., or less than 70° F. Further up country the range is much greater; on the Ghats the minimum temperature may be as low as 40° F., with a maximum sun temperature of 130° F.

In view of the fact that on the G.I.P. Railway it was not found necessary to re-site any of the signals in order to avoid their being obscured by the track structures, this necessity should not arise on lines similarly equipped in this country, seeing that trains on the G.I.P. Railway frequently ran at 70 to 75 m.p.h. during preliminary trials without any difficulty being experienced.

In reply to Mr. White, the question of erecting a steam generating station to supply power for the sections beyond the suburban lines was considered by the Railway

Board and the Railway Company. There were some negotiations with the Tata Companies, but I understand that at that time, when conditions were very different from what they are now, there was some doubt whether the Tata Companies would be able to meet the demand or could guarantee priority of supply in the event of a shortage of water following a bad monsoon. For this and other reasons it was decided that a special railway power station was necessary.

In the figures of costs given in the paper the word "capital" may be, as Mr. White mentions, somewhat misleading. Actually the figures given on page 935 should be referred to as "the gross cost," because no allowance is included for any credits on account of displaced locomotives and other material. However, the figures include all other items of cost, e.g. alterations to telegraphs and telephones, freight, customs duty, and other general charges.

In reply to Mr. Croft, no special arrangements were made in the design of the various locomotives to deal with excessive water condensation in the control and brake parts, and I am unaware of any experience to show that such special arrangements are necessary. I regret that I am unable to give precise figures which would show whether the so-called articulation between the trucks of the freight locomotives has been beneficial. In one case, as Mr. Croft mentions, the wear of the tyres on the locomotive from which the articulation had been removed was rather less than on other locomotives, but it would hardly be reasonable to conclude from this isolated case that the articulation was definitely harmful.

The results of the various tests which have been carried out to ascertain the resistance of passenger trains fail to show that this resistance drops after a period of continuous running. Of the three types of passenger locomotives, while there is some slight observable difference in the running at high speed, it would be difficult to say that any one is markedly better than the others.

It is not easy to form a conclusion as to the principal causes of the short-circuits that occur from time to time on the multiple-unit trains. An analysis of the operating records shows that the short-circuits arise from a variety of causes, as in all other trains of this type.

In reply to Prof. Catterson-Smith, I am unable to give any information as to the experience gained by the G.I.P. Railway in connection with the flood-lighting of their railway yards.

THE VARLEY BROTHERS: CROMWELL FLEETWOOD VARLEY AND SAMUEL ALFRED VARLEY.

By Lieut.-Col. A. G. LEE, O.B.E., M.C., B.Sc., Member.

(*Discourse delivered before* THE INSTITUTION *on the occasion of the Varley Centenary Meeting, 5th May*, 1932.)

INTRODUCTION.

It is generally recognized that considerable benefits are derived from the study of history, because it is said "history repeats itself," and we are supposed to learn from past events something which will guide us on the trackless plains of the future. Ordinary history, however, consists largely of records of war interspersed with periods of peace. The principal difference between these two is that one consists of "battle, murder, and sudden death," and the other is "envy, hatred, and all uncharitableness." We can but hope that history of this sort will not repeat itself, and we can be certain that, in the future, events of scientific discovery and invention will be of greater importance in controlling the course of the world's affairs. For this reason it is incumbent upon us to record these events and to set forth for future generations the progress of science and engineering.

There is, however, one important difference between ordinary history and scientific history: historical events of the ordinary kind were, as a rule, personal to an individual or group of individuals; they could not have been performed with the same effect by anybody else. In scientific history on the other hand, a discovery, if it had not been made by one individual, would almost certainly have been made by another, for scientific discovery is the discovery of truth.

We can, however, honour the men who make these discoveries and we can gain inspiration from their lives, their methods, their successes, and their failures. Only those who have attempted to do some pioneering work in science or engineering can realize the trials and tribulations of work on the frontiers of knowledge, and the devotion and energy which are necessary for tackling unsolved problems.

The year 1932 is the one-hundredth anniversary of the birth of Samuel Alfred Varley, and when I was invited to prepare a short lecture on his life and work I suggested that it might be as well to include an account of his brother, Cromwell Fleetwood Varley. Both brothers did pioneer work in telegraphy at the same period, and between their efforts there was considerable confusion, both at the time and subsequently. So much was this the case that in a letter from S. A. Varley to the *Electrical Review** in 1889, he refers to a paper read by him at the Society of Arts in 1859, "which created some attention at the time, and which led to his brother being offered the post of electrical engineer to the Atlantic Telegraph Co. (the offer being accompanied with the assurance that he might name his own salary)."

Some effort has been made to clear up the confusion between the work of the two brothers, but if it has failed in any particular instance it is hoped that the error may be set down to the difficulty of settling questions of authorship at this late date.

The brothers belonged to a family which for several generations had been interested in scientific and artistic pursuits, and it may be desirable to sketch in briefly the background from which they sprang. Their father, Cornelius Varley (1781–1873), was trained in the laboratory of his uncle, Samuel Varley, but he also became distinguished as a painter and was, with his brother John, one of the founders of the Water Colour Society. Cornelius was the son of Richard Varley, a man of some mechanical ability and considerable scientific attainments. The uncle of Cornelius, Samuel Varley, was a leading scientist of his day. He was interested in chemistry and other sciences, and as he required a large room for his experiments he took, in 1794, the celebrated Hatton House which had the reputation of being haunted. Here he carried on his work and with some friends founded a "Chemical and Philosophical Society," of which Josiah Wedgwood, among others, was a member. The members of this society afterwards formed the Royal Institution in 1800. Earl Stanhope, who was a patron of the Hatton House lectures, persuaded Samuel Varley to join him; the lectures thus came to an end and the Royal Institution sprang into existence.

Cornelius was in his uncle's workshop at the age of 12, and at the age of 14 had made himself a microscope, for which he ground his own lenses. He was awarded the Gold Isis Medal of the Society of Arts for his lever microscope, and in 1851 gained a prize medal for his graphic telescope. He contributed a number of landscapes to the Water Colour Society and exhibited up to 1859 at the Royal Academy. In 1821 Cornelius married Elizabeth Straker, a cousin of Miss Barnard, who became the wife of Michael Faraday.

Cornelius was an extraordinary mixture of artist, mechanician, and scientist, being prominent in each direction. He delivered the fourth Friday-evening discourse at the Royal Institution in 1826, Faraday having delivered the first of these lectures. He was a prominent member of the Society of Arts, the Royal Microscopical Society, the British Association, the Water Colour Society, and the Royal Institution.

The family are justly proud of their connection with Oliver Cromwell, through his daughter Bridget, who married General Fleetwood. The mother of Cornelius was a Miss Fleetwood, and the names Cromwell, Fleetwood, and Ireton, are found sprinkled among the

* *Electrical Review*, 1889, vol. 25, p. 485.

generation of the present century. S. A. Varley was known in his family by the name Alfred and he was much inspired by the fact that the later years of his life were spent at Winchester, the city of Alfred the Great.

Cornelius and his family were Sandemanians, and Cromwell and Alfred both attended the meeting-house about which we heard during the Faraday Celebrations, and which subsequently became the "North" telephone exchange. The Varleys looked upon Faraday with reverence in his dual capacity of religious teacher and scientist. They were indeed fortunate in being so closely associated with him in their early years.

The boys divided their playtime hours between their father's laboratory and his studio. Games of the ordinary sort were unknown to them, but they took great delight in experimenting with magnetism and other electrical phenomena, or grinding lenses for microscopes. The simple home life of the boys, with the inspiration they obtained from their father, prepared the way for their persistent, methodical, and patient work of later years. No distractions were allowed to interfere with their labours, and meditation became a habit.

There is one other member of the family to whom reference should be made, John Varley (died 1842), already mentioned as one of the founders of the Water Colour Society. John was a particularly successful water-colour painter, earning, it is said, in his palmy days over £3 000 a year. In addition to this success he was even more famous as an astrologer, and he is said to have cast a horoscope for his two nephews, Cromwell and Alfred, which ran somewhat as follows:—

He predicted for Cromwell a speedy recognition by the world of his scientific attainments and that he would die rich. Alfred on the other hand would not be honoured until his old age. His career would synchronize in a wonderful way with the destinies of his country, and in the later part of his life England would be engaged in a great struggle from which she would either emerge victorious or go down for ever.

As we now know, success came to Cromwell but not to Alfred. The latter fretted all his life through the neglect of his scientific contemporaries, and he only received scientific recognition when, in 1894, a movement was set on foot to obtain for him a Civil List pension. He lived until 1921, so that he saw England emerge victorious from the Great War.

For those who believe in horoscopes this little history may seem something more than a mere coincidence. It is also interesting as an example of the workings of heredity, astrology in one generation cropping out as scientific attainment in the next. Samuel Varley, the uncle of Cornelius, practised astrology, as also did Cornelius until he joined the Sandemanian sect, after which he thought it wrong to attempt to forecast the future. It was probably the blending of strong imaginative tendencies with scientific training which made the subjects of this discourse devote their lives to invention and the improvement of science.

Cromwell Fleetwood Varley, F.R.S. (1828–1883).

Cromwell Varley's early training and the example of his father gave him a taste for experimental work, which was destined to bear ample fruit in his later years. It is not surprising, therefore, that at school he found lessons irksome and that he took more interest in experimenting with such things as batteries than in performing the daily tasks. He was of good physique, and his skill in swimming enabled him to save the lives of five persons, for which he was presented with a testimonial by the Royal Humane Society. He was on board the steamer "Cricket" in 1847 when the boiler exploded. He was covered in an instant with steam and red-hot cinders, but without hesitation jumped overboard, sustaining no injury beyond spoiling a suit of clothes.

In 1846 he entered the service of the Electric Telegraph Co., and two years later was appointed assistant to the superintendent of outdoor work. This was before the days of gutta-percha insulation, and Cromwell appears to have developed special abilities for locating the numerous faults and repairing the wires. This early experience was responsible for his devoting his attention to the science of testing, of which his construction of condensers, resistance coils, and the discovery of the famous loop test, were the outcome.

The introduction in 1847 of gutta-percha-covered wires with their improved insulation gave Cromwell the opportunity of observing whether insulated wires could hold a static charge. With his brother Alfred he experimented with a 10-mile length of gutta-percha-covered wire, and concluded from these experiments that the condenser effect of the wires would offer serious obstacles to the transmission of signals over long distances. These views were not accepted by the company, which proceeded to establish long underground circuits between London, Birmingham, Manchester, and Liverpool. On the completion of these circuits the difficulties predicted by Cromwell were met with, and Faraday was called in to overcome them. Cromwell, however, had the honour of finding a solution in his so-called "double-current" system, in which a positive current to line was always succeeded by a negative current to counteract the charge on the wire. His first patent* covered the invention of a double-current key which earthed the line wire for a short interval between the application of the positive and negative currents. This system overcame all the difficulties. Cromwell was soon after appointed telegraphic engineer of the London district, and thenceforth became practically the electrical adviser to the company.

In August 1850 the first submarine cable was laid between England and France. It lasted only a few hours, but in this time messages were exchanged, one being sent to Louis Napoleon Buonaparte. This led to a rapid development of submarine cables in various parts of the world, and eventually a project was formed for laying a cable across the Atlantic. In 1856 the Atlantic Telegraph Co. was founded with this object.

It is difficult to realize at this date the almost insuperable obstacles which these early pioneers had to face. Nothing was known of the stresses to which a cable was liable in paying out or picking up, the best methods of testing to ensure absence of faults, the possibilities of corrosion, or the risk of damage by sea-worms and by

* Patent No. 371—1854.

chafing on rocks. All this knowledge had to be dearly bought.

The first attempts at laying an Atlantic cable were made by H.M.S. "Agamemnon" and U.S.S. "Niagara" in 1857 and 1858: owing to cable breakages these attempts were unsuccessful. On the 5th August, 1858, however, a cable was successfully laid and communication established. Although communication ceased on the 1st September, 732 messages had been exchanged in the meantime, thus proving the possibilities of the system. Before the cable broke down, the British Government had time to countermand the departure of the 62nd and the 39th Regiments, which were about to leave Canada for England, thereby saving about £50 000. This circumstance called popular attention to the advantages to be derived from telegraphic communication between distant lands.

The cause of the interruption was never precisely ascertained. Blame has sometimes been attached to the electricians for using induction coils 5 ft. in length to apply currents to the cable. Whatever the cause, Cromwell Varley, who had assisted in the investigation of the defects, became electrician to the company in succession to Mr. Whitehouse. In 1860 several attempts were made to raise the cable, but these were abandoned owing to the bad condition of the sheathing wires. The failures of the Atlantic Telegraph Co. and the Red Sea and India Telegraph Co. led the Government to appoint a committee in 1859 to investigate the whole question of submarine telegraphy. Half a million of money had been sunk in the Atlantic, and public confidence in the practicability of submarine telegraphy had been shaken.

The report of the committee (on which Cromwell represented the Atlantic Telegraph Co.) stated that the failures of the submarine cables were due to causes which could have been foreseen and recommended the conditions to be observed in the specification, manufacture, laying, and maintenance of cables. The report was published as a Parliamentary Blue-book. Sir Charles Bright, in his presidential address* to the Society of Telegraph Engineers, referred to this report as "the most valuable collection of facts, warnings, and evidence, which has ever been compiled concerning submarine cables."

By 1865 a considerable amount of fresh information on cable-laying was available. The Admiralty had sent expeditions to explore the Atlantic bottom, and the engineering problems involved in the construction and laying of cables had been the subject of continual research and study. Capital was obtained with some difficulty, but eventually all was ready for a fresh effort. On the 23rd July, 1865, the S.S. "Great Eastern" (22 500 tons) with Captain Sir James Anderson in command, Mr. Canning as engineer, and Mr. De Sauty, Sir William Thomson, and Cromwell Varley, as electricians, began paying out cable from Valentia towards America at a speed of 6 knots. Trouble soon arose, the first fault being experienced after 84 miles had been paid out. It was decided to pick up back to the fault, which was found to have been caused by a piece of iron wire which had pierced the cable. On the 29th July, after 716 miles had been paid out, another fault—caused by the same kind of defect as the first—was encountered. A third fault occurred at 1 186 miles: this time the cable had to be picked up in a depth of 2 000 fathoms, and 1 mile only had been recovered when an accident happened to the picking-up gear. The great ship, having stopped, was at the mercy of the wind and waves, and the cable was subjected to considerable stresses. Before the faulty portion could be secured on board, the cable parted and sank. An endeavour was made to pick it up by means of a grapnel, but although the cable was hooked a number of times the rope gave way on each occasion, and eventually the stock of grappling rope on board was used up. As a result the expedition had to give up hope and return to port.

To overcome financial difficulties the Atlantic Telegraph Co. now became amalgamated with the Anglo-American Telegraph Co., which was formed for the purpose of raising fresh capital for the next venture. On the 30th June, 1866, the "Great Eastern" sailed from the Thames for a further attempt to span the Atlantic. This time Cromwell Varley remained at Valentia as electrician. On the 13th July the ship commenced paying out the cable and with only a few minor accidents she arrived off Heart's Content, Newfoundland, 14 days later, bringing the expedition to a successful conclusion.

The "Great Eastern" sailed again on the 9th August to pick up the 1865 cable, the end of which lay about 600 miles from Newfoundland. After several weeks of failures, during which the store of grappling ropes steadily diminished, the cable was hauled aboard. Tests showed the cable to be sound, and immediately afterwards, in response to the ship's call, a reply was received from Valentia. The recovered end was spliced and the ship paid out anew towards Newfoundland, completing the laying on the 8th September.

Never before in the history of science had there been a like example of patient and persistent endeavour in the overcoming of such enormous difficulties, and these early pioneers set an example of courage and resource which has been a shining light to those who have followed them.

Sir William Thomson and Cromwell Varley entered into partnership at this stage as consulting engineers. They were joined later by Fleeming Jenkin, and the cable was worked under the patents of Thomson, Varley, and Jenkin.

It has already been mentioned that Cromwell devoted a good deal of attention to the science of exact measurement, and he was one of the earliest workers in this field. He constructed condensers and resistances, and in one of his early patents on this subject he refers to his units of resistance as "Varley" units, in the absence of any agreed name. In 1861 the British Association, at the instance of Sir Charles Bright and Latimer Clark, formed a committee with the object of determining a rational system of electrical units. Cromwell served on this committee, which in 1863 determined the value of the ohm. The *Telegraphic Journal** of 1864 gave a list of 11 different kinds of resistance units which were in current use at that time. Varley's unit was equivalent to the resistance of a particular piece of copper wire

* *Journal I.E.E.*, 1887, vol. 16, p. 32.

* *Telegraphic Journal*, 1864, vol. 1, p. 208.

$\frac{1}{16}$ inch in diameter and 1 mile in length. Later, in 1881, the first International Electrical Conference was held in Paris, and Cromwell Varley took part in the deliberations. This and later conferences in 1882 and 1883 determined upon the adoption of an international system of units based on the C.G.S. system, and practically identical with that which had been in use in England.

The famous Varley loop test was patented by C. J. and Cromwell Varley in 1859. As originally devised it employed a differential galvanometer in place of the Wheatstone bridge which is now used, but the principle of putting the fault at one of the points of balance and thus eliminating the effect of earth polarization was the essential and valuable part of the invention. A Varley testing set was still in use in 1899 at Mallow, Ireland, at the testing point of the Western Union circuits to America, and another was still in place at Limerick up to a few years ago. The Varley slide resistance was another of Cromwell's inventions: in it a derived or potentiometer circuit was placed across two coils and a tapping point on the shunt circuit allowed a finer subdivision to be obtained. This invention has played a prominent part in submarine cable testing.

In 1867 Cromwell was asked to report on the condition of the lines of the Western Union Co. of America. A copy of this report, engrossed in a beautiful and rather unusual style by the late Mr. J. D. Reid, is still in the possession of the company. The report bears the signature Cromwell Fleetwood Varley, and contains various appendices, tests, and suggestions.

Cromwell's activities in telegraph and other sciences covered a very wide field. He devised in 1861 a double-shed insulator for telegraph wires, with a view to obtaining better insulation in wet weather. He invented a galvanometer with a coil as the moving element, the coil being mounted with hairspring connections. The relay which bears his name, patented in 1856, utilized the principle of an armature magnetized from an external magnet, which had been introduced by Siemens in 1851. This type of relay is still employed in telegraphic work. Cromwell designed one of the first telegraph repeater systems, and his "mill" repeater, in which a small windmill was introduced to provide a delay action, was installed in 1856 at Amsterdam for the purpose of converting from his double-current system to the Continental single-current system. He invented a vacuum lightning protector, which was patented in 1861 and is now on exhibition at the Science Museum, South Kensington. He patented a static electricity machine, but this was superseded by the invention of the dynamo. In 1862 he patented the use of an artificial line in submarine cable work, basing his system on that described by his brother Alfred in 1859 before the Society of Arts. Cromwell's apparatus was demonstrated to the Royal Institution in 1867, but was only used for the purpose of testing the terminal apparatus of submarine cables, and when the invention of duplex was applied to submarine cables by Stearn in 1873 the Varley artificial line was used for the purpose of balancing the cable. In 1870 Cromwell invented the "cymaphen," a kind of harmonic telegraph in which tuning forks were used as the sending elements and vibrating wires, excited electromagnetically, as the receiving units. The cymaphen instruments used in his experiments at Fleetwood House, Beckenham, were described as "humming away like bumble bees possessed of deep rich bass voices."

Besides his inventions in connection with telegraphy Cromwell evolved an electrical method for locating metallic masses in the earth, and invented a coupling for repairing broken propeller shafts on ships, at that time a source of much danger and delay. Another of his inventions was the "chronopher," an appliance for sending out time signals on wires to various parts of the country. A modernized form of this system is still in use at the General Post Office. His activities also extended to the transmission of messages by pneumatic tubes, for the initiation of which Latimer Clark was largely responsible. Cromwell improved the system and laid pneumatic tubes in various towns, notably Liverpool —between Castle-street, the Royal Exchange, and Water-street.

Cromwell has been described as having been possessed in a large degree of that power of taking infinite pains which has been described as genius. He was a skilful designer and also had a gift for turning to practical account scientific ideas. He had a very clear perception of the essentials of a problem and the way in which it should be solved, and this, combined with almost volcanic energy, enabled him to bear down opposition and bring a project to realization. The success which attended his efforts was due in large measure to his personality, but the combination in him of inventive and business faculties was sufficiently unusual to be remarkable.

On the transfer of the telegraphs to the Government in 1870, Cromwell did not pass into State service but remained on consulting work.

Sir William Thomson, writing to the *Electrical Review** about Cromwell Varley, said "I well remember when I first made his acquaintance at Valentia in the autumn of 1858, when he was sent by my brother directors to co-operate with me in examining the cause of the failure of the cable after its short-lived success. I had been extemporizing resistance to measure the insulation resistance of the cable. He came with a box of resistance coils ready made—a thing not then generally known—quite unknown, I might almost say, amongst English practical electricians. . . . I look back with great pleasure and satisfaction to all my intercourse with Cromwell Varley, as a friend, during the eight years of work ashore and afloat for realizing Transatlantic telegraphy, in which both of us had the privilege of taking part."

Cromwell contributed a large number of papers to scientific gatherings, the Royal Society (of which he was elected a Fellow), the Royal Institution, the Institution of Civil Engineers, the Society of Arts, etc., and constantly took part in discussions. The *Proceedings of the Royal Society* for 1871 contain two interesting papers by him.† One describes experiments on the production of a luminous arch in an exhausted tube by placing the tube between the poles of an electromagnet. He states that, in his opinion, the arch is composed of attenuated

* *Electrical Review*, 1883, vol. 13, p. 204.
† *Proceedings of the Royal Society of London*, 1871, vol. 19, p. 236.

particles of matter projected from the negative pole by electricity, in all directions, but that the magnet controls their course. The other paper* deals with the polarization of metallic surfaces in water, and states that platinum plates immersed in a dilute solution of sulphuric acid have enormous electrostatic capacities, provided the e.m.f. is less than 1·7 times that of the Daniell cell. He deduced from this that the fluid is separated from the plate by a film of gas less than 10^{-9} inch thick.

In those pioneer days in the field of science, workers and thinkers came to the front, and telegraph progress during the constructive period up to the successful bridging of the Atlantic in 1866 was largely the history of the Varley brothers.

Samuel Alfred Varley (1832–1921).

Alfred Varley received his very early education from his father, and it was not until he had reached the age of eight that he was sent to St. Saviour's Grammar School, Southwark, where he remained until his 14th year. He acquitted himself fairly well as a classical scholar, but magnetism, chemistry, and electricity, claimed from him greater attention than his school books. After being kept back a long time in the first form he became convinced that he was being forced to remain there intentionally; one day, therefore, he attended the second form, and his resolute manner so carried the day that he was allowed to remain. Those were the days when a boy had to fight his way through school, and although Alfred was of a retiring and thoughtful disposition he possessed a good physique and was highly successful as a pugilist. Even at this date he reduced pugilism to a science, the axioms of which were: "Hit your opponent in the face. If he hits you do not take any notice of it, but go on hitting him in the face as often as you can." He became a leader of the rougher games, the best high jumper, the fastest long-distance runner, and the best all-round athlete in the school.

On leaving school he at once took up scientific research work. Between 1846 and 1849 he made several hundred Grove cells for his brother Cromwell's electric light experiments. Most of us who know what a messy job it is to set up and refresh primary batteries will realize that these efforts helped to turn his thoughts to magnetic machines as a source of energy. As the magneto machines of that period gave very indifferent results Alfred set to work to improve them. At the age of 17 he commenced the construction of a machine the field magnets of which were to consist of bundles of magnetized steel wires, the revolving armature being made of laminated iron with the coils wound round the middle. His efforts met with little appreciation, and as he possessed no proper engineering tools he discontinued his attempts.

In 1852, at the age of 20, he entered the Manchester workshops of the Electric Telegraph Co., which had been incorporated 6 years previously. In 1854 he was made engineer in charge of the Liverpool district of the company. Much of the work was new, and there was no previous experience to guide the telegraph engineer of that period. Of engineering training in the sense in which we now know it, there was none. The man on the spot had to deal with the faults which occurred, and this frequently meant developing new ideas and new methods to meet the needs of the moment. The time balls worked from Greenwich may be mentioned as an example of this. The first long-distance time ball was erected at Liverpool, and Alfred was called upon to correct its deficiencies. In this connection he designed an electric chronograph, probably the first of its kind, for measuring both the loss of time in the apparatus and the time occupied by the signal in travelling by wire from London. The apparatus which released the ball was so arranged that it sent a signal back to London when it had operated. Alfred found the interval of time between signalling from Greenwich and the dropping of the time ball to be $\frac{11}{20}$ sec., $\frac{9}{20}$ sec. being taken up in the passage of the signal from London to Liverpool and $\frac{6}{20}$ sec. in the apparatus at London and Liverpool. The experience gained on this work enabled him some years later to construct apparatus for use in India, China, and elsewhere. He effected considerable improvements in the relay apparatus for working the time ball, which were described in a paper in the *Telegraph Journal and Electrical Review*.* The weight of a time ball 6 ft. in diameter is not inconsiderable: this has to be released by an electromagnetic device, which in turn must be worked by the small telegraphic currents sent over the line wire. His solution of this problem was based upon compound-lever arrangements with a roller to avoid friction.

At the outbreak of the Crimean War, Col. Wylde, a retired officer of the Royal Artillery, was deputy chairman of the Electric Telegraph Co. At his suggestion the company offered its services to the Government for the purpose of laying and operating field telegraphs in the Crimea, and the offer was accepted. The equipment was designed by Latimer Clark, who was at that time engineer-in-chief to the company, Cromwell Varley being his assistant. It thus happened that Alfred was sent out to the Crimea as superintendent of the first field telegraphs ever used in warfare. He was present at the battle of Tchernaya and the evacuation of Sebastopol. In a letter from Therapia dated December 1855 he gives an interesting account of the dispositions of the field telegraphs, and states that the number of messages forwarded from headquarters averaged 15 to 20 per day and that the number received was about the same but some of them were very long and verbose. Gutta-percha-covered wires, buried just under the surface of the ground and therefore subject to numerous breakages, were employed, in conjunction with single-needle apparatus. Alfred recommended, however, that in future expeditions Morse instruments should be used on account of their greater reliability. After leaving the Crimea he was put in charge of the Varna-Constantinople cable, then the longest length of submarine cable ever laid.

On his return to this country he found telegraph engineers discussing various points in the design of submarine cables; it was generally thought that a higher speed of signalling would be possible on cables with small conductors than on those with large. Alfred read

* *Proceedings of the Royal Society of London*, 1871, vol. 19, p. 243.

* *Electrical Review*, 1880, vol. 8, p. 207.

papers before the Institution of Civil Engineers* in 1858 and the Society of Arts† in 1859 opposing the views which had been arrived at by the scientific advisers of the Atlantic Telegraph Co. Discovering that Faraday had given an explanation of the action of small conductors which upheld the views of the advisers of the company, Alfred sent him a copy of his paper. In reply, Faraday endorsed his views in a kind and flattering manner, adding that Alfred was well able to hold his own in electrical controversy.

The paper read before the Society of Arts defined the propagation conditions on long submarine cables and gave an account of an artificial cable line, consisting of condensers and resistances, which simulated the propagation conditions of a submarine cable. These artificial lines subsequently came into use for duplexing submarine cables, and they are still employed for this purpose. When preparing his Society of Arts paper he used to retire to his study and sit deep in thought for hours. For weeks beforehand he committed what was to him the extravagance of riding in cabs when travelling on business, so as to be able to ponder over his problems undisturbed. He did not finally commit his ideas to paper until the day before the meeting.

In 1866 he designed an improvement on the needle telegraph in which the magnetic needles were replaced by needles of soft iron rendered magnetic by induction from a permanent magnet. These needles were not liable to demagnetization by lightning, the great defect of the Wheatstone apparatus. The principle seems to have been covered by Cromwell in 1856, but he apparently did not construct the apparatus. Alfred also fitted the induced-needle galvanometer with continuously-moving contacts (the first of their type) and used it as a relay. One element of the contact consisted of a gold roller which was rotated continuously by clockwork, and the rubbing contact made by it with the other element eliminated sticking.

He took out a number of patents for train intercommunication by electrical means, and although his system was fitted both on the train in which Queen Victoria travelled to the North and on the trains of the London and North-Western Railway Co., it was not adopted generally. The last patent taken out by him in connection with this matter is dated 1885. He read a paper on the subject before the Society of Engineers‡ in 1873.

In 1859 he re-entered the service of the Electric and International Telegraph Co. as engineer of the London district. Two years later, however, he resigned this appointment in order to take over the management of a telegraph-manufacturing business inherited by his father, who was at that time over 80 years of age. Some of the patents taken out about this time bear the joint names of Cornelius and Samuel Alfred Varley, although from the age of his father it may be inferred that Alfred was the real inventor. This business finally failed after the Government had taken over the telegraphs in 1870, as the change meant that there was no longer sufficent work to keep the factory going.

In 1866 Alfred was able to complete some of the inventions on which he had been occupied for a considerable time. The needle telegraph, to which reference has already been made, was taken up and had a successful career. To this he added a lightning protector, named by him the "lightning bridge," which consisted of two electrodes immersed in carbon particles or a mixture of carbon and insulating powder. He found that such a mixture became conducting when a high voltage was applied to it, but was comparatively non-conducting to low voltages. This phenomenon was described in a paper* before the British Association in 1870. Alfred thus discovered the properties of the coherer, but it was left to others to re-invent and make use of the device in wireless telegraphy.

The greatest invention he made about this time was the self-exciting dynamo, on which he was to have read a paper at the Nottingham meeting of the British Association in 1866. He was, however, called upon to install his system of intercommunication on the train in which Queen Victoria was about to proceed to the North, and in consequence he did not arrive at Nottingham until the eve of the last day of the meeting. Although he was unable to present his paper, he mentioned the matter to Prof. Harley and Mr. Russell, and the latter advised him to describe the invention before the Royal Society as soon as possible. Had he done so his claims as the inventor of the dynamo would not have been questioned. His neglect of the advice, however, allowed Dr. Werner Siemens to be first in the matter of publication, for he read a paper before the Berlin Academy of Sciences in December of that year describing a dynamo. Sir Charles Wheatstone also invented a dynamo which, together with the Siemens dynamo, was described† to the Royal Society in February 1867. Alfred completed his machine in August or September 1866, a fact which was proved by the testimony of his friends to whom he had exhibited it. He took out a patent for his machine in December 1866, but allowed it to lapse. A second application in June 1867 was, however, granted. A considerable amount of controversy arose in later years as to who was the first inventor of the dynamo; but it may be taken that the question was decided in his favour, for in 1885 he was awarded the Gold Medal at the International Inventions Exhibition for "devising the first self-exciting dynamo machine."

The dynamo, thus started on its course, proved to be full of possibilities for the electrical industry, and Alfred worked unremittingly at the problem of improving it. Ten years after his discovery of the dynamo principle the idea of regulation came to him, and the result was the invention of the compound-wound machine in 1876. Unfortunately he allowed this patent to lapse in 1878.

The compound-wound machine was later the subject of a long-drawn-out legal fight in which Alfred championed the cause of the electrical industry against the claims of the Anglo-American Brush Corporation. Mr. Brush had been granted a patent for a compound-wound dynamo in 1878, and on this ground his company tried to suppress its competitors in the industry. Alfred

* *Proceedings of the Institution of Civil Engineers*, 1858, vol. 17, p. 368.
† *Journal of the Society of Arts*, 1859, vol. 7, pp. 302, 314, 329.
‡ *Transactions of the Society of Engineers*, 1873, p. 162.

* S. A. VARLEY: "The Mode of Action of Lightning on Telegraphs, and a New Method of Constructing Telegraph-coils," *Report of the British Association for the Advancement of Science*, 1870, p. 28.
† *Proceedings of the Royal Society of London*, 1867, vol. 15, p. 369.

endeavoured to arouse the interest of the industry by writing a series of articles in the *Electrical Review*.* Messrs. King, Brown, and Co., of Edinburgh, decided to oppose the Brush Corporation and the case was fought out in the Court of Session, Edinburgh, in November 1888, when judgment was given in favour of Varley's precedence in the invention of the compound-wound machine, the Brush patent being declared invalid. The case was then carried to the House of Lords, which in 1892 also decided in favour of Varley's patent.

Such was the contribution to the world of a man who worked all his life unweariedly at science, and whose efforts failed to realize any material reward. Far-sighted as he was in the application of science, he was unversed in business affairs. Thus he neglected to renew the patent for his dynamo and therefore failed to secure the financial reward which would necessarily have come to him. Mismanagement of business matters was his failing throughout his career, and he struggled on for a long period under conditions of poverty.

The failure of his factory in 1873, and other business worries, caused his health to suffer and enforced a long absence from scientific gatherings. This, no doubt, was one of the factors which led to the neglect of his work by his scientific contemporaries, who did not know him and who frequently confused his work with that of his brother Cromwell. In 1894, however, engineers and scientists, who up to that time had only grudgingly admitted his scientific attainments, secured for him a Civil List pension of £50; this was increased to £100 in 1896. It is pleasing to record that many of those who had opposed him earlier, rallied to his assistance in this matter. His life was to a large extent embittered by his failure to secure recognition by his brother-scientists, but even this late acknowledgment must have been a considerable solace to him in his retiring years.

The Institution.

Our Institution was founded in 1871, with Sir William Siemens as its first President, under the name of the Society of Telegraph Engineers. Among the 71 Founder Members were four representatives of the Varley family —Cromwell (Member of Council), Frederick, Samuel Alfred, and Octavius. At the opening meeting, on the 28th February, 1872, Cromwell Varley said† "This society, I assume, will gradually, by natural selection, develop more into an electrical society than into a society of telegraphy proper; and the moment it is understood that all papers on electricity, or bearing directly upon the development of electrical science, are admitted, it at once takes the science out of the narrow groove into which it seemed to be drifting, into the most extensive of all grooves, because it will be found ultimately to embrace every operation in nature." He has proved to be a prophet with a wide insight into the scientific and practical possibilities of electricity, and the march of events bears testimony to the wisdom of his prophecy.

Cromwell and Alfred both played a part in the up-building of the structure of electrical engineering, and the name of Varley will always be associated with the foundation stones of the edifice.

The author wishes to acknowledge his indebtedness to those who have kindly assisted in providing him with information as to the activities of the Varley brothers. In this connection he would particularly mention the Rev. Telford Varley and Mr. Percy Varley, sons of Alfred Varley. The Science Museum, the executors of S. A. Varley, Mr. Willoughby Smith, Mr. R. S. Whipple, and the Post Office, have provided the apparatus exhibited. The author is also indebted to the *Electrical Review*, which championed the cause of Alfred Varley, and to Sir Charles Bright's book on "Submarine Telegraphy," for much of the information contained in this discourse.

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* *Electrical Review*, 1887, vol. 21, pp. 583, 613, 630, 655.
† *Journal I.E.E.*, 1872, vol. 1, p. 34.

HIGH-FREQUENCY VALVE-OPERATED INDUCTION FURNACES.*

By H. HIRST, B.Sc.(Eng.), Graduate.

(ABSTRACT *of paper read before the* SHEFFIELD STUDENTS' SECTION *9th February*, 1931.)

For the efficient operation of induction furnaces it has been shown† that a certain relation must be observed between the size and resistivity of the material to be melted and the frequency of the electrical supply. Approximately, a certain quantity r/β must be greater than 3, where r is the radius of the charge in centimetres and

$$\beta = \sqrt{\left(\frac{\rho}{4\pi p}\right)}$$

ρ being the resistivity of the charge in electromagnetic units, and p the pulsatance ($= 2\pi \times$ frequency)

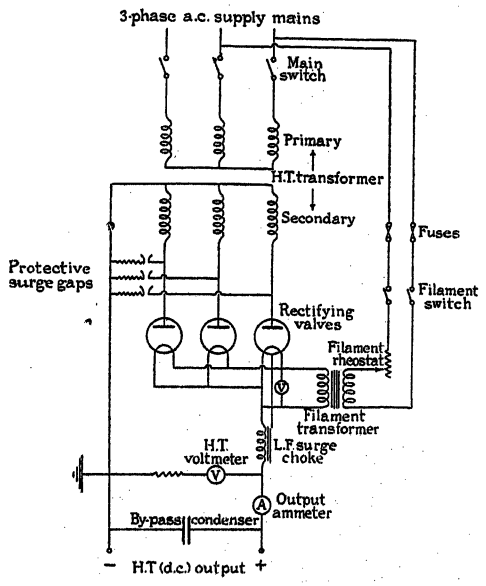


FIG. 1.—High-tension valve rectifier.

in radians per sec. It is seen that the larger the specimen to be melted and the lower its resistivity, the lower may be the frequency for efficient operation. In consequence, large furnaces of ¼ ton and upwards may be designed to run on frequencies of 500 to 2 000; small research equipments, however, especially where flexibility is required in respect of the material to be melted, operate on frequencies of 20 000 to 1 000 000.

In the latter type of furnace, the power at high voltage, usually 10 000 volts, is obtained from one or more water-cooled valves. Direct current is supplied to the valves from 2-electrode valve rectifiers. These may conveniently be of the 3-phase type, the connections being usually as shown in Fig. 1. The main transformer delivers an 8 500-volt 3-phase supply to the anodes of the rectifying valves, which, in their turn, provide a d.c. output of 0·75 ampere at 10 000 volts. The star connection of the transformer is made through three current relays, which protect the rectifiers from overload and also trip the main contactor should any dangerous condition arise, e.g. a short-circuit in either the oscillator or the rectifier unit, due to softening of, or mechanical damage to, the valves. A voltage relay is also fitted in the rectifier filament-circuit to ensure that the filament voltage is maintained at its correct value.

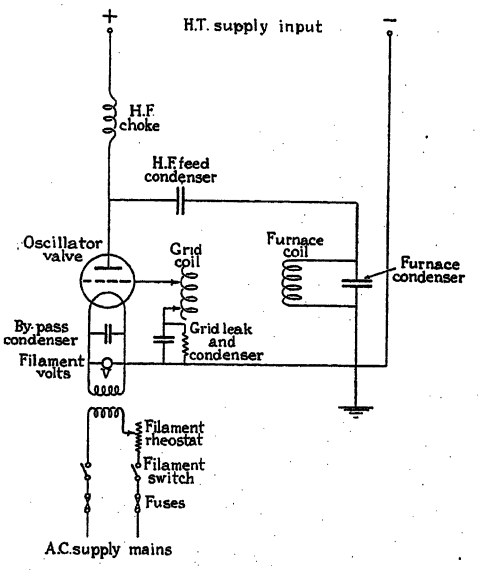


FIG. 2.—High-frequency generator and induction furnace.

The relays, together with the necessary instruments and push buttons, are mounted on a panel fixed at the front of the rectifier cubicle.

The high-tension current is led to the oscillator unit, shown in Fig. 2, by a thick copper strap. The oscillator valve is water-cooled. A water relay connected in the supply circuit prevents the filament and h.t. supplies from being applied unless the water flow to the valve is adequate. The oscillator-cubicle panel carries a filament control-resistance, filament voltmeter, grid-coupling control, and watt-hour meter. At the back of the panel is mounted the 10-kW valve, with an appropriate high-frequency choke, grid leak, grid coil, and condenser. A spark-gap is included in the anode lead to provide protection against surges.

The current is led from the oscillator unit to the furnace unit, which comprises the main oscillatory

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

† C. R. BURCH and N. R. DAVIS: "The Quantitative Theory of Induction Heating," *Philosophical Magazine*, 1926, vol. 1, p. 768.

condenser and the water-cooled inductor coil; the latter is made of turns of $\frac{1}{4}$-in. square copper tubing wound into a helix 3 in. in diameter. Each turn is fitted to three wooden uprights, so as to hold it rigid.

During operation, the oscillator valve is kept working efficiently by varying the number of turns on the grid coil. It is possible to stop the valve from oscillating by introducing a large charge of magnetic material into the furnace coil; this is avoided by lowering the charge gradually into the furnace coil until it becomes red-hot

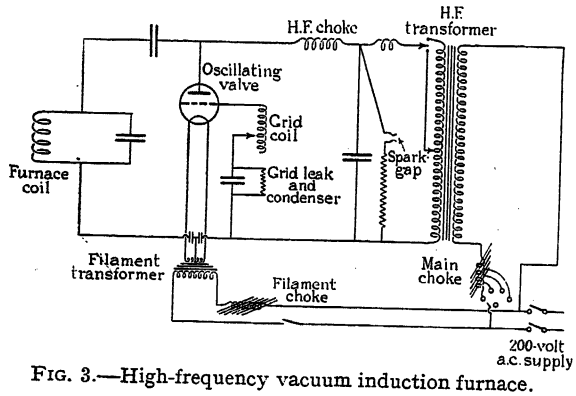


FIG. 3.—High-frequency vacuum induction furnace.

and non-magnetic. Power control is effected either by varying the high-tension supply by means of a choke or auto-transformer, or more simply by raising or lowering the inductor coil with respect to the charge.

For charges heavier than 1 lb., a tilting furnace has been developed to melt up to 10 lb. of metal. This takes the form of a wooden box containing the furnace coil, the crucible being kept in place in the centre of the coil by zircon sand or ganister. The crucible is tilted about the lip by means of a chain. To facilitate starting when melting magnetic material, a tap is arranged in the coil so that only a small portion of the latter may be used. When the charge is hot and non-magnetic the whole coil is switched in.

For melting reactive metals, where contamination by atmospheric gases is undesirable, a high-frequency vacuum furnace is employed. Fig. 3 shows the electrical connections. The valve supplies high-frequency current to the main oscillatory circuit, which is tuned to the frequency of the anode resonator circuit by altering the tappings on the grid coil as the temperature of the metal rises and its inductance increases. Grid bias is provided by the grid-condenser and grid-leak method. Measures are taken to protect the transformer from any sudden surges in the circuit. The power is controlled by a choke on the primary side of the transformer.

The furnace chamber consists of a silica tube, round which the heating coil is fitted, standing on a metal Langmuir oil-pump. The latter is backed by a 2-stage glass mercury-pump, which is in turn assisted by a rotary oil-pump and a water-pump. A tube containing phosphorus pentoxide to absorb water vapour is placed between the mercury-pump and the rotary oil-pump.

When metals of high vapour-pressure are being melted an electrode-less discharge occurs in the furnace tube, forming a shield around the charge and preventing electrical energy from reaching the metal. This difficulty is overcome by fitting a silica chimney to the crucible, whereby the glow is concentrated above the metal and prevented from hindering the heating of the charge. If the pressure in the furnace tube is allowed to rise above 5 cm the glow disappears. Melting in an inert atmosphere may therefore be accomplished, the gas being admitted through an inlet in the Langmuir oil-pump.

A high-frequency valve furnace at the National Physical Laboratory uses two valves on the "push-pull" system. The valves are each of 2·5 kW output, the anodes being supplied at 8 000 volts from a centre-tapped transformer. Oscillations are produced by magnetically coupling the anode circuit with a tuned grid coil. This furnace is principally used for carrying out thermal analysis, in which direction it has been very successful.

DISCUSSION ON "RECENT PROGRESS IN LARGE TRANSFORMERS." * And "THE APPLICATION OF THE INDUCTION VOLTAGE REGULATOR." †

SCOTTISH CENTRE, AT GLASGOW, 12TH JANUARY, 1932.

Mr. J. W. Rodger: With regard to the paper by Mr. Ayres, the problem of voltage control on a.c. circuits is to-day being solved by installing induction regulators, or regulating transformers with tappings connected to suitable switchgear, or regulating transformers with an arrangement for altering the leakage field between the primary and secondary windings. Induction regulators have a marked operating advantage over tapped transformers if a smooth voltage change is essential, but on the many supply systems where voltage variation in small steps is not objectionable tapped transformers can be used with an appreciable saving in first cost. Furthermore, the tapped transformer is less likely to be damaged by heavy load fluctuations or external short-circuits than is the induction regulator. Induction regulators have not been adopted in Great Britain to the same extent as in other countries ahead of us in the use of a.c. distribution. In America the induction regulator is a highly standardized piece of apparatus, and the designs described by the author follow very closely those developed by American manufacturers. The line-drop compensators used in connection with the automatically controlled induction regulators can also be applied with advantage to the control of regulating transformers. Impressions gathered during a recent visit to America indicated a tendency to dispense with the use of induction regulators —owing to their being rather unreliable in operation and comparatively expensive to install—and to substitute adaptations of tap-changing transformers. It would be of interest to know what steps are taken in the design of induction regulators to eliminate dangerous mechanical reactions between the two windings, coincident with heavy load fluctuations. The author suggested that there was a weakness in the construction of Brown-Boveri induction regulators in that a crank is used as a means of transmitting energy from the motor to the rotor of the induction regulator: this suggestion is unfair to the manufacturer in question, who has doubtless taken care of the point by so designing the equipment as to eliminate undue mechanical reaction between the rotor and stator of the regulator, thereby avoiding any undue stress on the crank.

Turning to Mr Charley's paper, the Buchholz relay is a good and sensitive method of protecting transformers, but it should be understood that its adoption is possible only on units especially constructed for its accommodation. As its action depends on concentration within the relay chamber of gases liberated following the development of a fault within the transformer windings, it can only be used on transformers fitted in tanks of the conservator type. Since the release of air bubbles from any part of the core or windings will cause the Buchholz relay to operate, it is essential to make provision at the time of installation for special treatment of the core and windings to ensure that no air bubbles are left after filling with oil. This may be somewhat difficult to arrange for in cases where transformers must be shipped without oil. Further, all air must be removed once again if for any reason the core and windings are lifted from the oil. Operation of the relay following an escape of air would leave the user in doubt as to whether a slight fault had developed or not, and he would be in a quandary regarding the advisability of lifting the core and windings for examination. In view of the above considerations it is not advisable to fit Buchholz relays to small transformers. In Germany and Switzerland the Buchholz relay is chiefly used in connection with large transformers installed at substations where all the necessary facilities are provided for vacuum treatment of the unit at the time of installation, and hence there is no danger of air being left trapped within the core or windings. A close inspection of non-resonating transformers similar to those described by the author shows that whilst the design may be theoretically correct, the undesirable complications of construction associated with it render the transformer liable to failure in operation. When one considers the numbers of large high-voltage transformers of normal design constructed by British manufacturers which are giving complete satisfaction in countries where lightning conditions are severe, there appears to be little justification for introducing the complication and increased manufacturing cost of the non-resonating construction. With regard to methods of cooling, the use on outdoor transformers of radiators constructed of gilled tubes appears to be bad practice. While manufacturing economies can be effected by the use of such radiators, which permit of natural siphon circulation on much larger transformers than can be cooled in this way if plain tubes are adopted, their satisfactory working depends on perfect contact between the inner edge of the gill and the outer surface of the tube over which it is wound. Any corrosion at the inner edge of the gill will impair the heat transference from tube to gill, and it is evident that such corrosion must eventually take place if radiators of this type are used out of doors. Normally the gill depends for contact on the tightness with which it is wound over the tube. The inner edge of the gill becomes corrugated during winding, and each corrugation forms a small pocket where water will collect and cause corrosion. It is therefore to be expected that transformers fitted with radiators of this type will in course of time develop dangerous temperatures if fully loaded.

Mr. P. A. McKillop: I should like to know what

* Paper by Mr. R. M. CHARLEY (see vol. 69, p. 1189, and vol. 70, p. 436).
† Paper by Mr. W. E. M. AYRES (see vol. 69, p. 1208, and vol. 70, p. 436).

method is adopted for lubricating the moving parts of the induction voltage regulator, as I have come across switches which would not operate owing to their being held fast by rust. We have recently been troubled by floods which have submerged our apparatus, and I should therefore like to know whether the induction regulator will work when immersed in water. Can the author inform me what British Standard grade of oil should be used to lubricate switchgear which has to operate at −40° F.? I should also like to know what provision is made for the proper cleaning of the coolers of large transformers on both the oil side and the water side, and what provision is made for emptying oil from such transformers.

Mr. A. P. Robertson: The paper by Mr. Ayres indicates that a single induction regulator connected to a line distorts the phase angle, and that double induction regulators are therefore necessary. This factor militates against the use of induction regulators on parallel feeders where each feeder has to be regulated independently, because if there are a number of feeders coming from a small substation which has not been originally designed for induction regulation, there will be insufficient room to accommodate the requisite number of induction regulators. If the feeders were not connected in any way, however, I think one regulator on each would suffice. What is the author's opinion on this point? I was interested in the slide showing an induction regulator on a tramway supply keeping the voltage on the lighting system practically steady. I do not think such a result would be possible in practice because the regulation would require to be very fast and the moving parts light. The rotor could not be made to move at a high speed, and, if the service were frequent, fluctuation on the lighting supply would be almost bound to occur.

With regard to Mr. Charley's paper, I should like to ask whether it is possible to design a transformer which will absorb harmonics (this is a sore point in Glasgow) and whether such a design would be very different in price and efficiency from the normal type. Regarding tap-changing, in the first design the 2-winding method was adopted; this involved the risk that one of the circuit breakers might stick open, leaving half the winding on full load and causing a burn-out of that half. It is interesting to see that this design is being superseded by the auto-transformer principle. What is the author's opinion regarding earth shields? These seem to have been almost completely abandoned, and the substitute for them is a very flimsy article. It is often placed inside the transformer, a dangerous practice because the arc formed when the apparatus operates causes the oil to carbonize. The apparatus sometimes contains a thin sheet of some insulating material such as paper or mica, and the leads inside the transformer have been known to be burnt out before the fault could be cleared. I think it would be much better if this piece of apparatus were put outside the tank. With regard to the question of transport, as the weight of oil contained in a large transformer is considerable I favour the filling of the tank with nitrogen for transport. This method is also cleaner. One of the author's slides showed a transformer being transported in a temporary tank, and I should like to know whether this unit was dried out before being put into the permanent tank. What was the voltage of this transformer? While I would not care to transfer a very high-voltage transformer from one tank to another unless it were dried out again, for voltages up to 11 000 volts there is not a great deal of danger in the practice.

Mr. R. McCulloch: I should like to know how the operation of the induction regulator affects the efficiency of the transformer.

Prof. S. Parker Smith: In my opinion many of the transformer designs shown by Mr. Charley are very ugly. One of the arguments in favour of the 5-core transformer is ease of transport, due to the lower construction of this type. Has the author examined the problem of the production of harmonics in transformers? Although the turbo-alternator has now reached a stage where it can produce little else but a sine wave, some supply authorities are not satisfied to leave well alone in this respect. Can the author give any information with regard to the relative proportion of harmonics in single-phase transformers in banks, in 3-limb, and in 5-limb transformers with the various 3-phase connections?

Mr. H. M. Stronach: In a compact area such as that of the Glasgow Corporation Electricity Department, where the 20 000-volt and 6 500-volt h.t. distribution is laid out so that the diversity between industrial and residential loads may be utilized in the main h.t. rings, the proper place for voltage regulation is on the low-voltage (440-volt) side of the transformers, or as close to the consumers' terminals as possible. Unless the Central Electricity Board object to operation of the on-load tap-changing gear on their transformers 6 or 8 times per day so as to follow the normal system load curve, the regulation of the 20 000-volt and 6 500-volt system can be controlled in this manner. Bearing in mind that the sites obtainable for 6 500/440-volt transformers are usually of very limited size, I should like to ask the author's opinion regarding the advisability of installing voltage regulators in such substations, where the low-voltage network can be interconnected to adjacent substations.

Mr. W. McFarlane: Can Mr. Charley give any relative flux-density figures for British transformers as compared with similar units manufactured in the United States and on the Continent?

[The authors' replies to this discussion will be found on pages 970 and 974 respectively.]

WESTERN CENTRE, AT BRISTOL, 11TH APRIL, 1932.

Mr. J. E. MacFarlane: I have heard of line troubles on the "grid" being attributed to high core densities (e.g. 17 000 lines per cm^2) in the transformers. Can Mr. Charley give any information on this point? On large transformers the thermal characteristics must call for special treatment: has it been found practicable to

use any of the new alloy sheet steels which have lower losses than stalloy?

Mr. W. A. H. Parker: Dealing first with the paper by Mr. Ayres, the Electricity Commissioners' Regulations stipulate that the declared minimum voltage of an e.h.t. supply must not be exceeded by more than 12½ per cent, and that for a l.t. supply the variation from the declared voltage must not be more than 4 per cent. If the l.t. supply is to be derived from e.h.t. mains, therefore, it is obvious that unless some form of regulating device is used the l.t. voltage cannot be kept within the prescribed limits if advantage is taken of the full 12½ per cent variation on the e.h.t. side. The induction regulator provides a ready means of ensuring that the voltage regulation is kept within the correct limits, and I believe that with automatic control it will serve a very useful purpose, especially in rural areas. We are finding induction regulators very useful on our own mains; but on an unbalanced 3-phase 4-wire distributor their cost is increased because either three single-phase units or a 3-phase unit plus a static balancer are required if reasonable regulation is to be maintained on all phases. This complicates the equipment, and where the power load is small we are therefore favouring l.t. single-phase supplies.

Turning now to Mr. Charley's paper, I am interested in the Buchholz device because it appears to make it possible to disconnect a faulty transformer from a line by means of simple mechanism, and I agree with the author that it ought to be incorporated in the protective scheme of every important transformer.

Mr. E. J. Davies: I should like to have Mr. Charley's comments on the gilled-tube type of cooling; in all the examples of this system that I have seen, corrosion can easily start between the gill and the tube, and the arrangement is such that it is impossible to clean and paint the tubes on site. Mr. Charley condemns the parallel-winding tap-changing system as obsolete. In view of the large numbers of transformers with this method of tap changing which are operating satisfactorily, his condemnation seems to be unjustified. The chief objection raised is the danger of burning out if the tap change is not completed. The possibility of an interruption during tap-changing is so remote, and the protection of the winding against such a contingency is so easy and certain, that this objection seems to be overrated. The parallel-winding method, however, seems to have an advantage over the reactor methods in that a smaller number of leads are brought out through the main tank. I have met with several cases where trouble has occurred on tap-changing connections passing through the tank, and it seems desirable to avoid these complications as far as possible.

Mr. W. Hill: Mr. Ayres emphasizes the fact that any alternative to an induction regulator requires a good deal of switchgear, on which trouble is practically always encountered owing to burning of the contacts. Has he considered the use of a small mercury switch of the newest type, capable of a million operations? Surely a plain transformer without a moving rotor is even more robust than an induction regulator, and it should give equal sensitiveness of operation since an equal voltage variation is necessary to operate the controlling relay.

With regard to Mr. Charley's paper, I am very interested in the Buchholz device, as more than once during lightning storms one or other of our transformers has apparently broken down. The fuses on the h.t. side are found to be blown; they are replaced, only to be blown again. It is often two or three days before we can get the transformer back into service again. An inspection by the makers usually fails to reveal the source of the trouble. The transformer is subjected to all the usual tests and is taken out of the tank and thoroughly dried. In some cases these transformers have been back in service for over a year after their breakdown. Can the author state what gases are given off by faulty transformers? There is clearly a wide field of use for the Buchholz device, and I should be glad to have further information as to the type of fault of which it will give warning.

Mr. F. de la C. Chard: Is it a fact that the nature of the fault causing evolution of gas in a transformer can be foretold from the colour of the gas accumulating in the chamber of the Buchholz relay? If so, one of the most important warning functions of the relay is lost when it is fitted to an unattended transformer. Have a beam of light and a photo-electric cell been employed in this connection to indicate, at the control point, the opacity of the evolved gas, in a similar manner to that employed for the inspection of furnace gases?

Captain P. F. W. Bush: When I was in the Federated Malay States as electrical and mechanical engineer to the Perak River Hydro-Electrical Power Co. I had actual proof of the effectiveness of the Buchholz relay. A large bank of 66/6·6-kV transformers fitted with this form of protection were being excited for the first time, and on reaching about half normal voltage the relay on one transformer operated, owing to a short-circuit between turns on the h.t. winding. Actually the relay was not connected electrically to the tripping circuit. However, the relay gave visible indication which enabled the oil switch to be promptly tripped out by hand. The damage resulting from the fault was quite local and was easily repaired on site.

Mr. Edward Jones: In my own personal experience I have come across several transformer breakdowns which would have been much less extensive had the units involved been fitted with the Buchholz device. No other form of protection appears to have such sensitivity for dealing with inter-turn insulation failure, as with the usual systems considerable damage is done before the protective gear operates. I should be glad if the authors could give the reasons why certain manufacturers are reverting to the use of non-inductive resistances instead of mid-point auto-transformers. I recently saw a 1 000-kVA 3-phase unit fitted with the former device.

[The authors' replies to this discussion will be found on pages 970 and 974 respectively.]

Mr. Charley's Reply to the Discussions at London, Newcastle, Birmingham, Liverpool, Manchester, Leeds, Sheffield, Glasgow, and Bristol.

Mr. R. M. Charley (*in reply*): I wish to thank the speakers for their valuable contributions to the various discussions of my paper, and I hope that there will be some response to my suggestions that papers should be prepared on special features appertaining to the general subject of transformer design and manufacture.

Where several speakers have discussed the same subject I propose to make a general reply without referring to the individual speakers by name.

The problem usually referred to as "harmonics and noise" is closely related to flux density in the transformer core. For magnetization of the silicon steel usually employed, the shape of the exciting current wave must incorporate certain odd harmonics, the most predominant of which is the third. The ratio of the magnitude of these harmonics to that of the fundamental increases very rapidly at flux-density values above those usually adopted. One speaker refers to a core flux-density of 17 000 lines per cm^2. I agree that it is very unreasonable to build a transformer with such a high value of flux density in the core, and where such transformers are installed trouble due to harmonics and complaints on account of noise are to be expected. However, I believe that, generally speaking, the transformers recently built in this country have been designed with reasonable core flux-density, and any incidental effects due to harmonics and noise should not be laid to the charge of the designers.

If one winding of a transformer is delta-connected a path is provided for a triple-frequency current, and consequently there is little likelihood of a third-harmonic voltage appearing on the system. The same principle naturally cannot be applied to higher harmonics, and hence it is inevitable that fifth- and seventh-harmonic voltages must appear in greater or lesser degree depending on the core flux-density. The effect of this on the system also depends to a large extent upon the characteristics of the transmission circuits, the load on the system, and the capacity of the generating plant running.

As regards noise, it is axiomatic that a laminated structure carrying an alternating flux, such as a transformer core, must vibrate and consequently emit noise. Assuming that the core construction is sound mechanically and that the tank and fittings are designed and built so that all extraneous vibrations are avoided, it is still inevitable that the core will emit a certain amount of noise. Although the fact of noise production is by no means new, the hum peculiar to large transformers is novel to the public of this country, where the size of units now being installed is several times that of transformers in service a few years ago, and these larger units are being installed out of doors. I suggest, therefore, that, assuming the transformers to be of a thoroughly sound and economical design, it will be necessary for transformer users and the public to adapt themselves to the inevitability of some degree of noise. It is true that the amount both of harmonics and of noise produced by a transformer can be reduced by using a lower flux density in the core, but this policy appreciably increases the cost and it is questionable whether it is justified.

Messrs. Holbrook and Abell speak in justification of the non-resonating design, and Mr. Holbrook gives some interesting information regarding the theoretical principle upon which the design is based. Mr. Abell quotes some figures showing the saving actually obtained by using a non-resonating transformer instead of an alternative design. In correspondence with Mr. Abell I have ascertained that his comparison refers to two transformers of similar capacity, both of which were tested at 265 kV; but (*a*) one unit was of the non-resonating type and was tested by inducing the test voltage in the winding, and (*b*) the other unit was fully insulated and was tested by applying the test voltage between the winding and earth from a separate source. I would point out that his statement is no justification for adopting the non-resonating scheme in preference to a design with inter-turn insulation based on B.S.S. No. 422—1931, for in the two examples cited the comparison is largely vitiated by other factors that are dissimilar and radically affect the design.

The remaining speakers support my claim that the non-resonating design for transformers may not do all that is claimed for it, and that there is no justification for the extra expense and complication. Furthermore, my recommendation that the British Standard Specification for inter-turn insulation should be universally adopted is strongly supported by several other designers, and I hope that users will adhere to B.S.S. No. 422—1931 in specifying their transformer requirements.

Several speakers criticize my figures (vol. 69, p. 1191) comparing the cost of 3-phase units with those of banks of single-phase units. While it is clearly stated in the paper that the figures apply to certain ranges of size and voltage, I admit that I should have pointed out that the difference decreases considerably for very large sizes. However, there must always be some advantage of cost and efficiency in favour of 3-phase units, and the fact remains that the popularity of 3-phase units is increasing all over the world.

Many speakers refer to the use of the Buchholz protective device, and some give interesting examples of its value as proved in service. It is suggested that the reason why the device is so popular on the Continent is that insurance companies have offered lower premiums for transformers equipped with it. As Mr. Sills remarks, "this fact seems to be an exceedingly good testimonial for the device." It is true that in the summer of 1931 the insurance companies in Germany reduced the premiums from 1·5 to 1·2 per cent of the value of the transformer, but this was only after the adoption of the device had become very general. Furthermore, transformer users had found the use of the device of so much value to them in reducing the cost of repairs, that they seriously considered not insuring such transformers at all unless the companies offered a considerable reduction

in premiums. There has been ample operating experience to demonstrate that transformers equipped with the Buchholz device sustain comparatively little damage when a fault occurs, and it has been shown that the repair costs of transformers so equipped are reduced by about 50 per cent. I consider, therefore, that the cost of installing the Buchholz device on transformers, particularly large units, is fully justified, and I hope that it will become more popular in this country.

With regard to Schedules I and II (vol. 69, pp. 1204 and 1206), giving particulars of transformers that have been made in various parts of the world, it was necessary to adopt some basis for the order of tabulation, and the natural basis was obviously kVA of unit. It was hardly feasible to take into account all the characteristics that affect size. I realized that no direct comparison between the various examples given could be made, and I gave the schedules merely to record typical examples of transformers built. I wish to thank Mr. Kennett for giving particulars of some 93 750-kVA transformers now being built for the Barking power station.

Some speakers ask for other data regarding the transformers mentioned in Schedules I and II or illustrated by slides; I regret that no such data are available. I wish to correct a typographical error in the weights given in Schedule I for the 42 000-kVA and 22 500-kVA units built by Messrs. Ganz and Co. (Budapest). The figures should be as shown in Table C.

TABLE C.

kVA of unit	Core and windings	Oil	Total
	tons	tons	tons
42 000	42	16	64
22 500	33	19	62

In connection with the discussion regarding the alternative methods of on-load tap-changing on large power transformers, Mr. Norris is almost alone in championing the parallel-winding scheme, but he is very fair in not giving undue weight to the fact that a large number of transformers having a total capacity of over 2 million kVA supplied for the national electricity schemes are built with this arrangement. In reply to Mr. Abell's request for information as to the number of cases where the parallel-winding scheme has given trouble, failures have probably not been numerous in comparison with the large total capacity of such transformers installed; but I claim that it is unnecessary for any particular design to fail in practice in order to render it obsolete, and for a new and better design to be developed. Mr. Abell mentions that in a 10 000-kVA 33-kV transformer with on-load tap-changing equipment there were 47 000 separate parts. It would appear that this transformer was somewhat complicated, considering its size and voltage. As another example I would quote the 45 000-kVA 132-kV transformer illustrated in Fig. 8, in which the total number of parts —including every washer and split pin—is 43 150.

While the consensus of opinion is in favour of the separate auto-transformer or reactor scheme of on-load tap-changing, Messrs. Diggle and Hill suggest variations of the arrangement described in the paper. I agree that there are advantages in the proposed alternative schemes, although they would all necessitate more tappings on the main transformer winding. However, it is possible that future developments may follow the lines suggested by these speakers.

Referring to the question of the maximum output of 3-phase transformers considered feasible in the early days of our national electricity schemes, Mr. Beard remarks that all designers were not enthusiastically in favour of larger 3-phase units. I did not, however, suggest that designers were unanimous in this policy; on the contrary, I stated that this advanced idea was only held by a few designers. In 1927, in the course of a discussion with a consulting engineer, I stated that a 100 000-kVA 132-kV 3-phase unit could be transported to site in its own tank.

In reply to Mr. Beard, I confirm that the ambient temperatures on which the curves shown in Fig. 9 are based are in accordance with the values laid down in B.S.S. No. 171—1927, viz. 40° C. for air and 25° C. for water. I agree that the result of this standard rating is, in countries where the ambient air temperature does not reach 40° C., that the transformers are not used to the maximum capacity. I heartily endorse the principle that the loading of transformers should be determined by measurements of actual winding-temperature rather than by readings of amperes. Mr. Beard asks me to suggest a period of short-circuit that might be assumed as standard in the design of current-limiting reactors. I suggest 5 seconds as a suitable standard period which would cover all probable conditions in service.

Mr. Ellis questions the curves given in Fig. 9, and he gives alternative figures in Table B. I cannot agree with his suggestion, and I believe that Fig. 9 represents the order of the relative costs of transformers with different types of cooling over the range of size indicated.

Mr. Kapp's remarks have been partially dealt with (vol. 69, p. 1231) by Mr. Ayres, the author of the paper on "The Application of the Induction Voltage Regulator" (vol. 69, p. 1208). In reply to Mr. Kapp's last question, I would say that there will probably be a limit to the voltage range for which on-load tap-changing can economically and reasonably be applied, but this range will probably cover all reasonable requirements. I can cite the case of a 24 000-kVA 66-kV transformer on which the voltage range is 27 per cent, and it is automatically controlled. The higher voltage-ranges naturally involve greater difficulty in the design of the transformer in respect of the variation of impedance (the upsetting of the symmetry of the windings causes undue mechanical stresses) and the increase in the number of tappings. On the other hand, if an induction regulator is employed there is no limit to the voltage range that can be obtained.

Mr. Venters asks a very reasonable question in regard to Table 2. For normal line insulators it is immaterial if the specified flash-over values are exceeded, but obviously for insulators installed to protect adjacent connected apparatus the value of the protection would be partly vitiated if the specified flash-over values were largely exceeded. On the other hand, there must be a big tolerance on actual flash-over values of insulation.

I suggest, therefore, that the figures given in the last column of Table 2 are minimum values, and that they should not be exceeded by more than 15 per cent.

Mr. Winfield questions my figures comparing the cost and losses of current-limiting reactors of the concrete type, and alternatively the copper-ring shielded oil-immersed type. Since the paper was written the ever-increasing demands for current-limiting reactors have produced intensive development, and it is now found that the magnetic shielded type and the ironclad type are more practicable and economical than the copper-ring shielded form. In any case, the cost and losses must be more than those of concrete-type reactors, but Mr. Winfield agrees with me that in nearly all cases the oil-immersed type is fully justified.

Referring to Mr. Jefferson's contribution to the discussion, I suggest that even if the winding-temperature indicating device were calibrated from readings taken by thermo-couple when the transformer was on test no greater safeguard would be secured. For all practical purposes the arrangement described in the paper gives a very close approximation to the actual temperature of the windings, and, at any rate, it is an infinitely safer means of indicating that a transformer is not being overloaded than a thermometer immersed in the oil. Any type of thermometer, e.g. an ordinary mercury thermometer or a resistance coil for distant indication, may be used with the device.

In reply to Mr. Rawll, road-transport contractors employ a permanent staff to investigate conditions over all possible routes and thus enable the best route to be selected. They must consider local by-laws and other legal conditions. Occasionally it is necessary to support bridges, to make up roads at corners, and sometimes even to remove tramway poles and trolley wires. Road transportation will probably never be restricted to a permanent loading gauge such as applies to the railways. Referring to Mr. Rawll's question concerning the position of the oil pump in coolers, I would explain that in a water-cooled cooler the oil has to be forced against an appreciable back pressure, maintained in the cooler for the purpose of ensuring that any leaks that may develop shall be from oil to water and not from water to oil. Hence the best position for the oil pump is before the oil inlet to the cooler, whereas in the air-blast type of cooler as illustrated in the paper the oil pump merely accelerates the flow of oil against very little resistance, and for reasons of physical location it is preferable to mount it in the outlet from the cooler.

Replying to Mr. Duffield, I confirm that large transformers are usually provided with jacking lugs, and haulage contractors are now expert at handling the most unwieldy loads under the worst possible conditions. A little forethought in determining the station lay-out and approaches might, however, considerably reduce the transport charges in many cases.

Mr. Robinson points out that the inter-turn insulation tests given in B.S.S. No. 422—1931 are less severe than those generally applied previously, and he asks on what grounds it is expected that better service will result from the adoption of the new specification. I wish to emphasize that the period of test demanded in the new specification is 10 seconds, whereas previously a 3-second test was generally required. It is certain that tests lasting for 10 seconds are more reliable than similar tests lasting for 3 seconds, and for equal insulation strength it is obvious that the longer the test period the lower should be the test voltage. Furthermore, the original inter-turn insulation tests usually called for were quite arbitrary, whereas the new standard specification has been completed on the basis of very extensive research.

Replying to Mr. Breach, in the copper-ring shielded type of reactor the rings are in close contact with the tank wall and are not insulated thereform. The rings are of ample cross-section in relation to the current that is induced by the leakage flux, and the flow of this current keeps the flux out of the tank wall to a great extent—thus preventing local heating of the tank. Mr. Breach does not agree that concrete-type reactors are becoming unpopular. The fact remains, however, that the number of oil-immersed reactors being installed is increasing very rapidly. Mr. Breach refers to the problems of safeguarding the tertiary winding of a star/star-connected transformer. I would explain that the capacity of the tertiary winding and the reactance between the latter and the high-voltage and low-voltage windings must be considered in relation to the general system conditions, such as earthing of the neutrals and direction of supply. In some special cases the tertiary winding should have the same capacity as the main windings, whereas in other cases a winding of very small capacity is sufficient. Whatever the precautions taken in the design, however, trouble is bound to overtake the transformer if, when a serious fault occurs on the system, thus causing heavy currents to flow in the transformer windings, the circuit breakers installed to protect these windings refuse to trip.

Prof. Teago gives a very interesting discussion of the theory of oscillating phenomena in transformer windings. I regret that I cannot at present give representative characteristics which could be used in a further investigation of the theory.

In reply to Mr. Mellonie, I suggest that since several million kVA of transformers with on-load tap-changing gear are giving satisfactory service, there is no cause to fear that system short-circuits may cause failure of the tap-changing gear. I will go further and say that tap-changing gear of the type provided on the transformer illustrated in Fig. 8 would operate without damage even when there was a severe fault on the system. I agree that there is no objection to purifying the oil in a transformer while it is on load, and I suggest for serious consideration the installation of a small purifier as a permanent attachment to all on-load tap-changing equipments. The fairly frequent use of this purifier would render unnecessary the opening-up of the equipment for overhaul, except after very long periods.

Mr. Metz asks several questions, to which I would reply as follows. Shipment of transformers in dry air under pressure has been proved to be very satisfactory. The inert gas in an "Inertaire" transformer undoubtedly reduces fire risk. It has been suggested that the Buchholz device could be used on a transformer not provided with an expansion vessel, by fixing a dome-shaped shield at the top of the tank under the oil so

that all gas would be collected and then led to the device. Such an arrangement, however, would obviously give rise to serious difficulties of construction, and hence it is necessary that all transformers to be protected with the Buchholz device should be provided with expansion vessels. My remarks in the paper regarding current-limiting reactors refer equally to section and feeder reactors.

In referring to the problem of inter-turn insulation Dr. Miller quotes an interesting table showing a comparison between various different designs. The data would have been of much greater value if comparative costs had been added. There is no question, however, that Cases 4 and 5 are very much more costly than either of Cases 1, 2, or 3, and I re-affirm my view that there is no justification for the adoption of any design that involves more expense than that for a transformer built with insulation in accordance with B.S.S. No. 422—1931.

In reply to Mr. Solomon, I regret that I cannot give further particulars of the 32 000-kVA transformer built by Messrs. Savoisienne. The current-limiting reactors mentioned on page 1203 (vol. 69) are for bus-tie service, in which case a load factor of 50 per cent is much too high; probably 5 per cent would be nearer the fact.

Mr. Skinner describes a type of concrete reactor in which a lead-covered cable is entirely embedded in concrete. I agree that this type does not labour under all the disadvantages ascribed to the open concrete-type construction, but I am sure that for all except very small sizes the cost of this construction would be even greater than for the oil-immersed type. The formula which I gave for the temperature-rise of current-limiting reactors (vol. 69, p. 1203) is derived from the fundamental expression for the increase in temperature of a material when all the heat is generated and stored in the material itself, and the various constants were determined from numerous tests. As regards the inherent reactance of transformers, there is a small range of values over which the cost is little affected, but outside this range the cost would increase. For a reasonable design, bearing in mind performance and cost, I suggest the following approximate values of reactance for normal 3-phase 50-cycle transformers:—

1 000 to 2 500 kVA	.. ..	5 to 6 per cent
2 501 to 7 500 kVA	.. ..	6 to 8 per cent
7 501 to 12 500 kVA	.. ..	8 to 10 per cent
Above 12 500 kVA	.. ..	10 per cent

I wish to reply to Mr. Bailey's questions as follows. The costs on which the curves given in Fig. 9 were based included coolers and all auxiliary plant. Referring to Fig. 10, I do not use the terms "safe-load indicator" or "hot-spot indicator." I agree that the temperature of the hottest spot must vary with different designs, and this point must be left to the designer. Nevertheless I claim that the winding-temperature indicating-device described in the paper gives a much safer indication of the thermal conditions of the winding than a thermometer located in the oil. In essence, the breather used on an "Inertaire" transformer consists of a device for drawing the air from the atmosphere through chemical agents which first extract all moisture and then deprive it of its oxygen: there are mercury seals to control the in and out breathing. When the transformer is first installed it is usually charged from a cylinder of nitrogen. Referring to the tests specified for inter-turn insulation in B.S.S. No. 422—1931, these were determined on the basis of research on materials commonly used in transformer manufacture. If insulation between turns is properly designed in respect to its relative puncture and creepage strength it will certainly be much better able to withstand a surge, in spite of the change in the ratio of capacitance to inductance.

I agree with Mr. Higgins that the larger transformers must be returned to the manufacturer's works should any repair become necessary, but I do not see why there should be any more difficulty in doing this after a number of years than immediately after manufacture. I suggest that the life of a transformer is probably more a function of economics than of the possible period of time for which it will continue to operate.

In reply to Mr. Logan, the number of cores used in connection with an on-load tap-changing equipment will not be further increased if no demands are made for features other than simple control and indication. The simplest scheme of control and indication for a pair of transformers requires 13 cores.

I do not support Mr. Lydall's view that wire-brush cleaning is satisfactory. All tanks should be sand-blasted, and the subsequent cleaning can be done quite well.

In answer to Mr. Robertson's query I would say that earth shields should on no account be used. Whenever possible the system neutral should be earthed. Otherwise an earthing device might be installed, but it should be located outside the tank. A reliable device is available for low-voltage circuits.

Replying to Mr. Davies, the gilled-tube type of cooling does not appear to be economical, and it is open to the objection that corrosion along the joint between the gill and the tube will make the cooling effect of the combination much less than that of a plain tube.

Mr. Chard makes the interesting suggestion that a photo-electric cell might be used in a Buchholz device to give at a remote point an indication of the opacity of the gas collected. It is questionable, however, whether the value of the scheme would warrant the expense.

Mr. Jones states that certain manufacturers are reverting to the use of a non-inductive resistance instead of a mid-point auto-transformer for on-load tap-changing. I would explain that it has always been general practice to use a resistance for the smaller transformers.

[The reply of Mr. Ayres will be found on page 974.]

Mr. Ayres's Reply to the Discussions at Liverpool, Manchester, Sheffield, Glasgow, and Bristol.*

Mr. W. E. M. Ayres (*in reply*): Mr. Norris asks for an explanation why feeder-voltage regulation has not been so universal in this country as in the United States. Bearing in mind the logic of the economic aspect of the application of induction regulators, it is difficult to give a satisfactory explanation. Conditions are not fundamentally different in the two countries. Probably the explanation is to be found in a combination of two rather English traits—the manufacturer unwilling to tackle a market until it is established, and the user "muddling through" until he is forced by circumstance to improve his services. The last few years have seen a great improvement against both these attitudes, although there is still a large number of supply authorities who admit their voltage troubles but refuse to take any action until forced by complaints. In America this has not been so. Distribution engineers have realized the value of service in popularizing demand and increasing revenue.

I cannot agree with Mr. Rodger's remarks to the effect that induction regulators are losing favour in the U.S.A., as the latest returns from that country show a maintained activity and development. Actually larger units have been built in this country than in America, but although on-load tap-changing holds the field there for large outputs, the induction regulator claims the field for the distribution (2 300 volts) as distinct from the feeder service. Far from being "rather unreliable in operation," the users of this class of apparatus would speak of its amazing reliability. The maintenance cost is negligible. Mr. Rodger is also under a misapprehension in thinking that the tapped transformer is less likely to be damaged by heavy load fluctuations or external short-circuits. Suggestions of this nature—as to the unsuitability of induction regulators to withstand such service conditions—have appeared from time to time in the technical Press and in some manufacturers' publications. There are induction regulators in this country of 360 kVA internal rating designed to withstand the throughput of 150 000 kVA under fault conditions, and I should be prepared to stand alongside the regulator while such a test was being made. When a fault occurs, an automatic regulator attempts to keep the voltage up. Would Mr. Rodger as confidently stand beside some of the tap-changing transformers while they operated under fault conditions of similar proportions?

This leads up to the question raised by Mr. W. Hill concerning the use of mercury-type switches. Whilst there are a few makes of wonderfully reliable mercury-tube switches which will withstand a very large number of normal operations within the rating for which they were designed, none of the manufacturers of these switches pretends that they will stand operation under fault conditions. For this reason, from an operating engineer's point of view, I would hesitate to use them on the high-tension side of any appliance which required an appreciable rupturing capacity.

Mr. Carr's remarks and his examples of unusual regulator applications are very interesting. I cannot, however, find any justification for the duplication of limit switches. Such limit switches can easily be designed for quick resetting when the rotor moves from the limit position, particularly with the mercury-tube type of switch, which requires a very small angle of tilt.

When the paper was first written the thermal-storage cooker referred to by Mr. Sills had not appeared on the market, and I now gladly modify my statement in this connection. Electric cooking forms an appreciable load in itself, and provides a large increase in load factor due to diversity. It is a load to be encouraged, but it is useless unless the supply voltage is maintained within a small margin of the declared value. With regard to the cost of losses shown in the Table on page 1215 (vol. 69), many urban district supplies are being purchased at a unit charge closely approximating to 0·5d., and these are the very cases where such a line 12 miles in length has to be run to tap off a neighbouring bulk supply. The regulator would be most economically placed at the sending end of such a feeder, from the point of view of both capital cost and line loss.

Mr. Mellonie and other speakers rather lightly assume it to be always feasible to transmit such an amount of power at 33 000 volts. They consider the problem from the point of view of their own undertakings, where a 33 000-volt supply is available. Such cases are in the minority, and to step up to 33 000 volts for such a load, with the necessity of stepping down twice before the consumers' terminals, would be more costly and less efficient. The examples given in the paper are from actual experience.

Mr. Porter is puzzled by the neutral choke shown in Fig. 14 (page 1214). A static balancer may quite rightly be installed to provide a local fourth wire, and such an appliance is sometimes used to provide an earth point for a delta 3-wire system. These remarks, however, apply more strictly to h.t. systems where the out-of-balance load is small or non-existent. On a l.t. distributor feeding a domestic load including cookers and radiators, the out-of-balance is often very considerable. Without the choke there should theoretically be more perfect balancing, as the function would be shared between the static balancer and the transformer. The point of balance, however, would be located somewhere between the two pieces of apparatus, the precise situation depending on the relative impedances. When a regulator is used we want the point of balance to be at the balancer and not at some remote point; hence the choke. If the neutral is cut, in place of the choke, the continued fourth wire is not earthed, and a phase fault to earth can cause a dangerous rise of voltage on consumers' premises. As Mr. Porter remarks, there is nothing in the Electricity Regulations to enforce the use of a

* Mr. Ayres's reply to the discussions at London, Newcastle, and Birmingham, will be found in Volume 69, p. 1230.

continuous conducting neutral; but the Regulations are so worded that in the event of an accident the undertaker is deemed to have taken insufficient precautions if the neutral is not of this type.

Dr. Wall and Mr. Robertson ask about the high-speed, oil servo-motor-operated regulators. These are of a very special design and are necessarily expensive. In addition, they can only be used in small or medium sizes on account of the large regulator load torque. The statement on page 1209, col. 1, is partly empirical, but depends essentially upon the maximum number of conductors per slot which is practicable for manufacture. Regulators have been proposed for the purpose suggested by Dr. Wall, but I am not aware of an actual application.

DISCUSSION ON

"HEAT LOSSES DUE TO LOAD CURRENT IN DIRECT-CURRENT ARMATURE WINDINGS."*

Mr. H. W. Taylor (*communicated*): Fig. A is offered as an alternative to the author's Fig. 8 to show how the current density varies in a conductor during and after commutation. The curves were made some time ago by the method described in my paper on "Eddy Currents in Stator Windings,"† where similar cinematographic representations were given of current distributions in alternating-current conductors placed in slots. The conductor considered in this figure was rather shallower than that taken in the author's Fig. 8. It had a value of $|ah|$ equal to 1·4, corresponding approximately to a conductor 0·5 in. deep undergoing commutation 100 times per sec. The commutating zone was 12 degrees (electrical). The currents in the conductors for the conditions considered do not become appreciably uniform until 60 electrical degrees after the middle of commutation, and a rough investigation showed that with a conductor having double the depth the current distribution would not become sensibly uniform before the next period of commutation was about to begin.

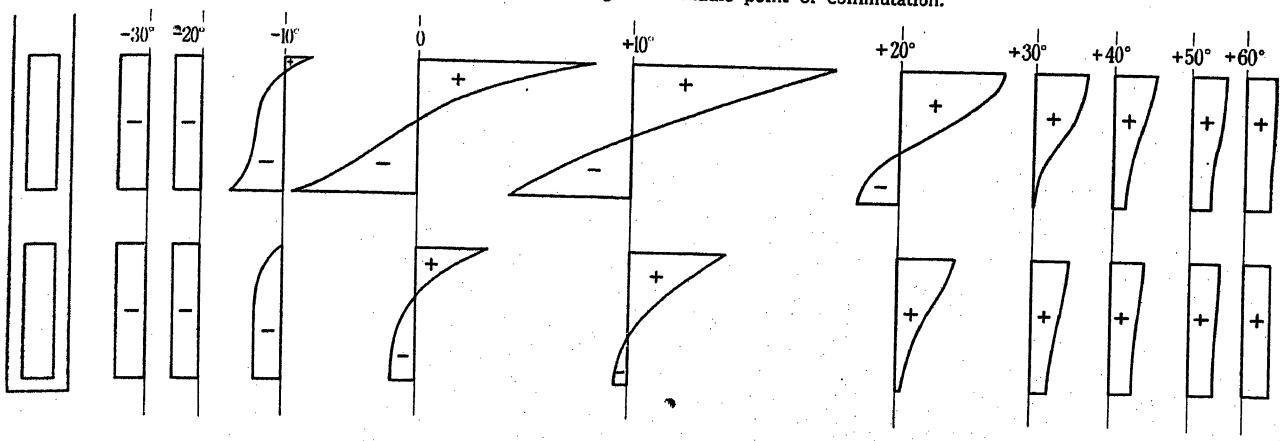


FIG. A.

Mr. E. A. Hanney (*in reply*): Mr. Taylor's method of presenting the results of Fig. 8 is informative and is a valuable addition to the paper. I believe that the very simple method of Fig. 8 is advisable in a first introduction to this phenomenon in a d.c. machine; Mr. Taylor's cinematographic presentation affords further insight and completes the mental picture. It is of interest to note that Mr. Taylor's conclusions from his figure are in agreement with mine.

Regarding methods of presentation, it may be mentioned that still another way is given in the discussion on the American paper quoted in the Bibliography (Item 41).

* Paper by Mr. E. A. HANNEY (see page 263).
† *Journal I.E.E.*, 1920, vol. 58, p. 295.

PROCEEDINGS OF THE INSTITUTION.

831ST ORDINARY MEETING, 10TH MARCH, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 3rd March, 1932, were taken as read and were confirmed and signed.

The President announced that, during the month of February, 561 donations and subscriptions to the Benevolent Fund had been received, amounting to £227. A vote of thanks was accorded to the donors.

A paper by Mr. J. Bruce, Associate Member, entitled "Modern Boiler Plant" (see page 541), was read and discussed.

The meeting terminated at 7.45 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

832ND ORDINARY MEETING, 17TH MARCH, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 10th March, 1932, were taken as read and were confirmed and signed.

Messrs. R. N. Pegg and J. Venters were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 283) had been duly elected and transferred.

A paper by Messrs. R. O. Kapp, B.Sc., Member, and C. G. Carrothers, B.Eng., Associate Member, entitled "Faults, and their Clearance on Large Networks" (see page 685), and a paper by Messrs. H. Pearce, B.Sc.(Eng.), Member, and T. T. Evans, Associate Member, entitled "Some Notes on Oil Circuit-Breaker Design and Performance" (see page 703), were read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

833RD ORDINARY MEETING, 31ST MARCH, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 17th March, 1932, were taken as read and were confirmed and signed.

A paper by Messrs. H. Blades and A. C. MacQueen, Associate Members, entitled "The Change-Over of Low-Tension Distribution Systems from Direct Current to Alternating Current" (see page 737), was read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

834TH ORDINARY MEETING, 7TH APRIL, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 31st March, 1932, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of March, 353 donations and subscriptions to the Benevolent Fund had been received, amounting to £191. A vote of thanks was accorded to the donors.

A paper by Dr. F. Lüschen, entitled "Modern Communication Systems" (see page 776), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

835TH ORDINARY MEETING, 14TH APRIL, 1932.

Mr. J. M. Kennedy, Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 7th April, 1932, were taken as read and were confirmed and signed.

A paper by Major E. H. E. Woodward, M.C., T.D., B.Sc.(Eng.), Member, and Mr. W. A. Carne, B.Sc.(Eng.), Associate Member, entitled "An Analysis of the Costs of Electricity Supply, and its Application in Relation to Various Types of Consumers" (see page 852), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

836TH ORDINARY MEETING, 21ST APRIL, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 14th April, 1932, were taken as read and were confirmed and signed.

Messrs. A. Fuchs and H. W. Taylor were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 403) had been duly elected and transferred.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. J. I. Bernard, F. A. East, and W. A. Ritchie, were appointed scrutineers of the ballot for the election of new Members of Council.

The President presented the Faraday Medal for 1932 (eleventh award) to Sir Oliver Lodge, D.Sc., F.R.S., Honorary Member, who expressed his appreciation of the honour conferred upon him by the award of the Medal.

Dr. W. E. Sumpner, Member, then delivered the 23rd Kelvin Lecture, entitled "The Work of Oliver Heaviside" (see page 837).

A vote of thanks to the lecturer, proposed by Mr. Ll. B. Atkinson, seconded by Col. Sir Thomas F. Purves, O.B.E., and supported by Sir Oliver Lodge, D.Sc., F.R.S., was carried with acclamation.

The meeting terminated at 7.32 p.m.

837TH ORDINARY MEETING, 28TH APRIL, 1932.

(Joint Meeting with the Institute of Transport.)

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 21st April, 1932, were taken as read and were confirmed and signed.

A paper by Mr. F. Lydall, Member, entitled "The Electrification of the Suburban and Certain Main-Line Sections of the Great Indian Peninsula Railway" (see page 911), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

EXTRA ORDINARY MEETING, 5TH MAY, 1932.

(Varley Centenary Meeting.)

Mr. J. M. Donaldson, M.C., President, took the chair at 6 p.m.

A short discourse (see page 958) on the lives and work of Cromwell Fleetwood Varley (6th April, 1828) and Samuel Alfred Varley (22nd March, 1832) was delivered by Lieut.-Col. A. G. Lee, O.B.E., M.C., B.Sc., Member.

After the Rev. Telford Varley had addressed the meeting at the President's request, a hearty vote of thanks was passed to Colonel Lee for his interesting lecture.

The meeting terminated at 6.45 p.m.

60TH ANNUAL GENERAL MEETING, 5TH MAY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 6.45 p.m.

The notice convening the meeting was taken as read. The minutes of the Ordinary Meeting held on the 28th April, 1932, were also taken as read and were confirmed and signed.

Messrs. W. R. Hackworth and S. Handford were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the list (see page 540) had been duly elected and transferred.

A list of the Premiums (see page 143) which had been awarded by the Council for papers during the session was read by the President.

The President next summarized the Annual Report of the Council (see page 24) and moved its adoption, which was seconded by **Mr. Ll. B. Atkinson.**

The President also announced that the Council had reduced the membership subscriptions to the pre-war rates and that this would cost the Institution some £2 300 a year.

Mr. D. J. Bolton: I should like to ask if it is proposed to do anything with regard to *Science Abstracts*. I notice that out of five or six hundred subscribers there has been a reduction of 100. At this rate, in five years' time there will be no subscribers at all. I suggested a year ago that the subscription to *Science Abstracts* should be included in the membership subscription, as it is, I believe, in the case of one or two other institutions. I should like to suggest, as an alternative to making no charge for *Science Abstracts*, the lowering of the price, in view of the fact that the cost of printing an additional few hundred copies would be slight.

The President: This matter has been raised on a previous occasion, but there is no reason why it should not be raised again. It will be referred to the Finance Committee for consideration. I thank you for the suggestion.

Major T. Rich: Would it not be convenient to split up the *Journal* so that the proceedings of the Wireless Section and of the Meter and Instrument Section could be sent only to those who really want them? I believe that it would save a considerable amount of printing.

The President: A suggestion on the same lines was made at a meeting of the Papers Committee to-day. One recognizes that it may be necessary later on to sectionalize the *Journal*; but to do this is not quite so easy as might be imagined. Anyhow, the matter is being considered by the Papers Committee.

The resolution in regard to the adoption of the Annual Report was then put to the meeting and was carried unanimously.

Mr. E. Leete (*Hon. Treasurer*): I have to move the adoption of the Statement of Accounts and Balance Sheet for the year 1931 (see page 34). In doing so, I wish first to turn to the Revenue Account. The year's working shows a deficit of £427 13s. 7d., against an approximate surplus in the previous year of £7 311. These two figures added together nearly correspond to the amount which has been debited to the Accounts under review in connection with the Faraday Centenary Celebrations which were held in 1931, the sum being £7 803. In addition, there were other non-recurring items—the flood-lighting, the memorial plaque to Sir Joseph Swan, and a donation towards the Ampère Memorial Museum—which add up, with the Faraday Centenary expenses, to £9 311. If the year had been a normal one there would therefore have been the usual satisfactory surplus. The total expenditure for 1931, including these non-recurring items, was £45 964, and if we compare this with the expenditure for 1930, namely £38 113, which included the extra expense of redecorating the Library, we find that the two figures are practically the same. Management increased by £454, but there was a saving on the building of £1 364. In 1930 there was a special expenditure, as I have just mentioned, in regard to the redecoration and the relighting of the Library, and in 1931 there was the installation of flood-lighting. In this last year we decided to transfer to the Repairs Suspense Account £1 000 instead of £1 500, and the net result is the saving which I have just mentioned, namely £1 364. There was a slight saving in regard to the *Journal*, which was nearly offset by fewer sales and advertisements, but the *Students' Journal* in 1931 cost us more, as it was for a whole year. The figure is £684, which is what was expected. The *Proceedings of the Wireless Section* in 1931 cost practically nothing. *Science Abstracts* cost £384, which was an increase of nearly £230. In connection with these publications I think emphasis should be laid on their value and importance, in the hope that they will be more widely appreciated. The cost of the Institution meetings was £147 more. This was due to increased activity; and the cost of Local Centres was also up, for the same reason, by £168. Scholarships were £475 more, owing to the gradual expansion of the original scheme. With regard to special grants, those made to the British Standards Institution and the Electrical Research Association have been maintained, and the total figure is less by £193. It is to be noted that the legal expenses have now been reduced to a normal figure, and are £308 less than last year, when the claim of the Institution for exemption from income tax was successfully defended. The income for the year was £46 300, as against £45 423 for 1930. This represents an increase of £877, which was partly due to the amount received from subscriptions, whilst dividends and interest received amounted to £5 581, as against £4 683 for the previous year. In 1930, however, there was an additional sum representing income tax refunded for previous years, so that the difference is only the amount which I mentioned just now, namely £877. Turning to the Balance Sheet, it will be seen that the position is satisfactory. The deficit already referred to of £428 has been carried to the General Fund, and because of the cost of the Faraday Centenary Exhibition and of the other non-recurring items, the use of cash on the Assets side, namely for the purchase of the last two investments, which amount to £4 920, and of the retention of cash in Australia and New Zealand owing to exchange difficulties, and of rather larger amounts owed by debtors, there was at the end of the year an overdraft at the bank of £8 644. The amount of the overdraft was intermittent, and it was extinguished early in January 1932, but it cost the Institution during the year somewhere about £40. As already noted, on the Liabilities side of the Balance Sheet the amount transferred to the Repairs Suspense Account was reduced from £1 500 to £1 000, since experience has shown that the former figure was excessive. The usual depreciation on the Library and furniture has been allowed, and the sinking fund for the replacement of the value of the building at the end of the lease is proceeding normally. The two investments just referred to were made in the early part of the year before the Institution was called upon to pay the expenses of the Exhibition. The General and Reserve Fund investments at the end of the year stood at £112 663. Their market value at that time, as noted on the Balance Sheet, was a little over £101 000. A fresh valuation at the end of last month shows, however, that the valuation is £113 613; in other words it is very nearly £1 000 above cost. I think these figures show that the position is sound financially. I should like again to take the opportunity of placing on record my appreciation of the efficient work and co-operation of all those in the Accounts section of the Institution. Furthermore, I must warmly thank Mr. Rowell for his courtesy throughout the year when I have asked him for information from time to time. I have much pleasure in moving this resolution: "That the Statement of Accounts and Balance Sheet for the year 1931, as presented, be received and adopted."

The resolution was seconded by **Mr. J. M. Kennedy.**

Mr. W. R. Rawlings: I think that the Institution is to be congratulated upon the result of the year's working. The only criticism I have to make is that with an income of something like £46 000 we allocate only £1 000 to the British Standards Institution and a similar amount to the Electrical Research Association, two bodies which do a good deal in the best interests of the industry and require help. I should like to suggest that the Council consider whether they cannot in the future allocate to these two organizations rather more money than they have done in the past.

The motion was then put to the meeting by the President and was carried unanimously.

The President: I am very pleased now to propose "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) the Hon. Secretaries of the Local Centres; (*b*) the Local Hon. Secretaries abroad; and (*c*) the Hon. Treasurer, Mr. E. Leete."

Mr. A. L. Lunn having seconded the motion, it was put to the meeting by the President and was carried with acclamation.

Major T. Rich then moved "That Messrs. Allen, Attfield and Co. be appointed auditors for the year 1932–33." The motion was seconded by **Mr. D. J. Bolton** and was carried unanimously.

The meeting terminated at 7.35 p.m.

THE BENEVOLENT FUND.

34TH ANNUAL GENERAL MEETING, 5TH MAY, 1932.

Mr. J. M. Donaldson, M.C., President, took the chair at 5 p.m. The notice convening the meeting was taken as read. The minutes of the 33rd Annual General Meeting held on the 14th May, 1931, were also taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1931 (see page 40) were presented and, on the motion of the Chairman, seconded by Mr. Ll. B. Atkinson, were unanimously adopted.

On the motion of the Chairman it was resolved that Mr. J. Attfield, F.C.A., be appointed Honorary Auditor for the year 1932.

The Chairman reported that, under Rule 15, the Council had appointed the following Committee of Management for the year 1931–32:—

The President (*ex-officio*).

Mr. R. A. Chattock,
Mr. E. W. Hill,
Mr. J. F. W. Hooper,
Mr. R. H. Schofield,
Mr. J. W. J. Townley,
Mr. R. S. Whipple,
} representing the Council;

Mr. J. R. Cowie,
Mr. A. L. Lunn,
Mr. W. R. Rawlings,
} representing the contributors;

and the Chairmen of the Local Centres in Great Britain and Ireland.

REPORT OF THE COMMITTEE OF MANAGEMENT OF THE BENEVOLENT FUND FOR 1931.

CAPITAL.

The Capital Account stood on the 31st December, 1931, at £17 811 17s. 2d., which is invested.

RECEIPTS.

The Income for 1931 from dividends, interest, and annual subscriptions, was as follows:—

	£	s.	d.
Dividends on investments ..	821	3	6
Interest	26	16	6
1 453 Annual Subscriptions ..	808	11	6
	£1 656	11	6

In addition to the foregoing, the Fund benefited during the year by the following amounts, many of which are non-recurring donations:—

	£	s.	d.
I.E.E. War Memorial Fund (balance) ..	326	9	5
I.E.E. Entertainment Fund, Summer Meeting in London	272	7	6
Mersey and North Wales (Liverpool) Centre, Golf Tournament	87	5	1
South Midland Electrical Engineers' Ball Committee	70	0	0
"Dynamicables"	52	10	0
Electrical Engineers' Ball Committee ..	50	0	0
British Electrical Development Association (proceeds of carnival at Newcastle-on-Tyne)	36	13	4
"Twenty-five Club"	26	5	0
Henley's Telegraph Works Co., Ltd. ..	25	0	0
Western Centre	17	3	1
North Midland Electrical Engineers' Ball Committee	15	0	0
China Local Centre	10	10	0
General Electric Co., Ltd.	10	10	0
Incorporated Municipal Electrical Association	10	10	0
Incorporated Municipal Electrical Association Golf Tournament	6	3	0
Messrs. Kennedy and Donkin	10	10	0
Messrs. Mavor and Coulson	10	10	0
J. D. Dallas	10	0	0
W. B. Esson	10	0	0
T. W. Sampson	10	0	0
Scottish Centre, Entertainment Fund ..	10	0	0
Sir George Sutton, Bart.	10	0	0
J. D. Butcher	6	5	0
C. R. Belling	5	5	0
E. C. Clark Nichols	5	5	0
E. Fawssett	5	5	0
Sir Hugo Hirst, Bart.	5	5	0
T. B. Mackenzie	5	5	0
S. R. Mullard	5	5	0
L. Murphy	5	5	0
L. Pariseau	5	5	0
C. S. Taylor	5	5	0
E. J. Wade	5	5	0
G. J. Websdale	5	5	0
North Midland Centre	5	2	0
L. C. F. Bellamy	5	0	0
S. G. Brown	5	0	0
"C2"	5	0	0
H. H. Couzens	5	0	0
J. M. Donaldson, M.C.	5	0	0
H. E. Morrow	5	0	0
G. H. Nisbett	5	0	0
W. J. Robertson	5	0	0
E. A. Short	5	0	0
M. A. Traynier	5	0	0
and 3 047 donations of under £5 ..	1 054	0	9
	£2 260	9	2

The accumulated balance of the Income and Expenditure Account amounted on the 31st December, 1931, to £2 649 14s. 7d., of which £1 000 3s. was invested, £550 was on deposit with the Institution Bankers, and £980 2s. was on Current Account for the purpose of meeting the cost of a new investment, which was completed a few days later.

Donors and Subscribers.

Lists of the names of donors and subscribers are issued to members of the Institution annually.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and to intimate that, apart from donations, the Committee will be grateful for annual subscriptions of any amount. The Committee are anxious that the Capital Account should be steadily augmented, so as to strengthen the financial position of the Fund.

Legacy.

The Committee have to report a legacy of £100 from the late Mr. E. Garcke, Member, which amount has been invested.

Grants.

Applications for assistance were made by or on behalf of 44 persons during 1931, and the Committee, after due consideration, made grants in 38 cases.

The total amount of the grants was £1 870 7s. 6d.

Wilde Fund.

The Capital Account stood on the 31st December, 1931, at £3 049 16s. 2d., all of which is invested and brings in an annual income of about £113 2s.

The balance standing to the credit of the Income Account (from which, under the Trust Deed, full Members only can benefit) on the same date was £200 4s. 7d.

No grants were made from this Fund during the year.

INSTITUTION NOTES.

Papers published in the Journal.

In view of the great increase in the number of papers submitted to the Institution and in the cost of printing and distributing the *Journal*, it has been decided that in future the length of a paper must not exceed 15 000 words and, whenever possible, be kept as far as practicable below that figure.

Tables of Complex Circular and Hyperbolic Functions.

The Elektrotechnischer Verein has recently issued a volume of new 4-figure tables of complex circular and hyperbolic functions. These have been computed by Hawelka under the direction of Prof. Emde. Compared with previously published tables they possess the advantage of progressing by small steps and giving differences whereby accurate interpolation is made possible. The descriptive text is in German, English, and French, in parallel columns. The principal tables are sin, sinh, cos, cosh, tan, tanh, cotan, and cotanh $(x \pm jy)$, by steps of 0·02 for both x and y. The volume, which also contains an extensive bibliography of the subject, can be obtained, price 15 Marks, by non-members of the Verein on application to the Geschäftsstelle des Elektrotechnischen Vereins, Bismarckstrasse, 33II, Berlin, Charlottenburg 4.

Membership Transfers.

The following transfers have been effected by the Council:—

Associate to Graduate.

Bancroft, Herbert Douglas.
Clewett, William Henry.
Penstone, Walter St. George.

Student to Graduate.

Aitken, James Glendinning.
Anderson, Horace.
Arnold, William Eli.
Ashton, Norman.
Atkinson, George Elliot L.
Bailey, Colin.
Bailey, Hugh Philip V.
Bana, Minocher Bejonji.
Bates, Joseph Leslie.
Belcher, Cecil Albert.
Bennett, George, B.Eng.
Bertenshaw, Norman Wright, B.Sc.Tech.
Boag, John Wilson, B.Sc.
Boul, John Edward.
Bowyer, Kenneth Charles.
Bradley, Reuben Stephen.
Brash, Eric Bayliss, B.Sc.
Brett, Edward James.
Bridgewater, Thornton Howard.
Bristow, Kenneth Walter, B.Sc.(Eng.).
Broadbent, Maurice Edward.
Brook, John Lewis.
Brown, Edmund Arthur L.
Burston, Ronald Frank.
Cameron, Ewen, B.Sc.
Campbell-White, Edward Cecil.
Challans, Benjamin William S., B.Sc.(Eng.).

Student to Graduate—continued.

Chaloner, Benjamin Sutcliffe.
Chrisp, Joseph Henry O.
Clark, Jabez Stanley.
Clarke, Robert.
Coates, Raymond Henry, B.Sc.(Eng.).
Cole-Baker, Brian Mortimer.
Coles, Raymond Scofield, B.Sc.
Court, Wyborn Percy N., B.Sc.(Eng.).
Davis, Robert Courtney.
Denholm, Norman Harold.
Dixon, Charles John E.
d'Ombrain, George Lee, B.Sc.(Eng.).
Dubash, Mahiar Dhanjishaw, B.Sc.
Eldred, Robert James, B.Sc.(Eng.).
English, Robert Lawrence, B.Sc.
Evans, Arthur Emlyn, B.Sc.
Fenwick, Christopher Evelyn, M.Sc., B.E.
Garrity, Harold Andrew.
Giese, Frederico Guillermo.
Gilchrist, James.
Gorman, Mervyn Edwin.
Grant, Robert Steel, B.E.
Green, Leonard.
Griggs, Edward Clement.
Grove, David Stevenson.
Hall, Fred, B.Sc.Tech.
Harker, Maurice Geoffrey, B.Sc.(Eng.).
Harvey, John Philip, B.Sc.(Eng.).
Hearn, John.
Hollis, Alfred Charles.
Horn, James Kawarau, M.Sc., B.E.
Horridge, Arthur.
Horsfield, John.
Horsington, Leslie Richard.
Hughes, Denis Hawxby.
Hughes, Henry Hugh, B.Sc.
Innes, James Albert.
Isaac, Francis Clifford.
Jamieson, Douglas.
Johnson, Eric Robert.
Johnston, Alexander Findlaytor.
Jotwani, Chimandas Khemchand.
Journet, Robert Edwin.
Katzelis, Nicholas George.
Kemp, James, B.Sc.
Khanna, Ram Charan L.
Kirkup, Ralph William.
Krishna, Mylapore Bala C.
Kumarsamy, Pattakan.
Lee, George Wallis.
Lennane, Wyndham Quin.
Lewis, George David.
London, Peter.
MacMillan, John.
Makinson, John Owen.
Marsh, Arthur Hireson.
Marsh, John Henry, B.Sc.(Eng.).

Student to Graduate—continued.

Martin, Thomas George.
Matthews, Theophilus Francis.
Meadows, Frederick Percival, B.Sc.
Mitry, Wadie, B.Eng.
Moir, James.
Munsi, Prodyat Kumar.
Murland, James Robert W., B.Sc.(Eng.).
Newsam, Harold, B.Sc.(Eng.).
Noble, Henry Royce, B.Eng.
Norman, Sidney John.
Oddy, Arthur Herbert S., B.Sc.(Eng.).
Oommen, Adangaprathoo, B.A., B.Sc.
Palethorpe, Wilfred, B.Sc.
Parker, Harry.
Patel, Raojibhai Bhailalbhai.
Pilkington, Garnier David.
Pinney, Gerald.
Pritchett, Richard Maurice B.
Raine, John Stanley.
Rajanayagam, Sabapathippillai, B.Sc.(Eng.).
Ramamoorthi, Begur.
Reynolds, George Alan.
Rivas, William Aloysius.
Sadleir, Cedric William M.
Salisbury, John Edward.
Scudamore, Charles John W.
Smith, Dick.
Smith, Francis Harwood.
Smith, John Watson.
Sreenivasan, Vellore Ranganatham.
Stebbing, Geoffrey Charles.
Stiff, Charles George.
Sumner, Walter.
Sutton, Gerald John.
Thadani, Shamdas Tharumal, B.Sc.Tech.
Thomas, Frederick John B., B.Sc.(Eng.).
Thompson, Geoffrey Philip.
Thompson, William Stanley.
Tomar, Ratansingh Ragunathsing.
Turner, David Asher, B.Sc.(Eng.).
Vardy, Jonah, B.Sc.(Eng.).
Wafa, Elsayed Hassan, B.Sc.
Walmsley, Francis Charles
Wardell, Sidney Humphrey
Warwick, George Alan.
Watts, Basil Kingsford.
Wickremesinghe, Mervin Lionel, B.A.
Wijeyeratne, Charles Maxwell F.
Willy, John Reginald.
Wilson, James.
Wilson, John Charles.
Wood, Reginald Logan.
Worsfold, Ivor Christopher M.
Wragge, Colin Gordon.

OBITUARY NOTICES.

PERCY FREDERICK ALLAN was born in 1881 and received his technical education at Armstrong College, Newcastle-on-Tyne, and at University College, London. He served an apprenticeship as a mechanical engineer with, and was afterwards employed by, Messrs. Palmers Shipbuilding and Iron Co. He was then for a few years with Newcastle Corporation (as a charge engineer), Messrs. Kennedy and Jenkin, Messrs. A. F. Yarrow and Co., and the Clyde Valley Electric Power Co. (as sales engineer). In 1910 he joined the staff of Siemens Brothers Dynamo Works, Ltd., at their London office, and in the following year went to Australia as acting general manager for their Australasian business. During the greater part of the War period he was employed by the Government on inspection duties. In 1919 he joined the Macintosh Cable Co., being appointed their northern area branch manager. After eight years in Newcastle he was transferred to the cable factory at Liverpool, as works manager and engineer. In October 1930 he joined the staff of British Insulated Cables, Ltd., as personal assistant to Mr. Nisbett, the managing director of the company, and was engaged particularly upon investigations in connection with the co-ordination of the company's numerous interests. He died on the 30th November, 1931. He was elected an Associate Member of the Institution in 1910 and a Member in 1920, and from 1924 to 1927 he served as Hon. Secretary of the North-Eastern Centre. He sat on many of the Institution's technical committees and all those with whom he came in contact were impressed by his strong personality, energy, and ability. He was a staunch friend, and his premature death has been deeply felt by all who knew him well. H. B. P.

BERNARD ARTHUR BEHREND died on the 25th March, 1932, at Wellesley Hills, Mass., at the age of 56. Born at Villeneuve, Switzerland, on the 9th May, 1875, he came of pioneering engineer stock, for his father was closely identified with the starting and early development of the sulphite process in paper-making, and founded the Hammermill Paper Mills in Germany, and at a later date those of the same name in Erie, Pa. Though one of a large family, Behrend forged a solitary way from an early age. He was educated partly by private tutor and for a period in England, and becoming an earnest student of English literature and of the writings of Huxley, Darwin, and Mill, he developed a strong Anglophile leaning, which grew stronger with the passing years. His technical training for the C.E. degree was obtained at the University of Berlin, and he studied also in Paris and London. One of his first appointments was as engineer assistant to Gisbert Kapp, towards whom he always retained a feeling of the warmest friendship and respect. He joined the Oerlikon Co., Switzerland, in January 1896, where he became assistant chief engineer; and, being in charge of the testing department there, as well as engaged on the design of all types of a.c. and d.c. electrical machinery, was able to develop and verify his theoretical deductions. One of his early discoveries was the relationship between the phase and magnitude of the primary current in a leaky transformer with negligible primary resistance, as exemplified for induction motors by his circle diagram, used universally to this day. It had been in the summer of 1895 that, proceeding on the methods expounded by André Blondel for dealing with magnetic flux components, he produced the circle diagram and disclosed it in a lecture, but its further publication was delayed until the issue of the *Elektrotechnische Zeitschrift* of the 30th January, 1896, after trials on an actual motor had verified the soundness of the theory. While several workers have been credited with the authorship of the diagram, it goes most appropriately under the name Behrend or Behrend-Blondel. Taking up his residence in the United States in the summer of 1898, he occupied himself for some 18 months in finding his footing, and during the interval lectured on a.c. design at the University of Wisconsin. He joined the Bullock Electric Manufacturing Co., of Cincinnati, Ohio, in January 1900, and soon became chief engineer. This company, which had previously made only d.c. apparatus, under Behrend's guidance rapidly developed a.c. equipment, including salient-pole alternators and induction motors, along such lines that, except for output per weight, they would have looked modern only a few years ago—before fabricated structures came into vogue. Even turbo-alternators were tackled as early as 1903, and a number were built in 1904. A Bullock-Hamilton set was exhibited at the 1904 Louisiana Purchase Exposition and a gold medal was awarded to Behrend for this and other exhibits, including the 40-pole 25-cycle alternator of 21 ft. bore which carried the Exposition lighting and power load and was popularly christened "Big Reliable." For turbos, he used from the start radial-slot rotors (giving C. E. L. Brown the credit) and, in addition, chrome-nickel steel end-rings, two features adopted by other large manufacturing companies many years later. The acquisition of the Bullock Co. by Allis-Chalmers about the beginning of 1904 brought Behrend into contact with Edward D. Adams, an association which led to long-continued friendship and mutual respect between the quiet engineer-philosopher and the financier, industrial, and railroad magnate. Behrend became chief electrical engineer to the combined company, and consulting engineer to Allis-Chalmers Bullock, Ltd., of Montreal. He left the Allis-Chalmers Co. in 1908. At that time the Westinghouse Electric and Manufacturing Co. was under the guidance of E. M. Herr, as receiver, who later became president; and his far-seeing colleague, Harry P. Davis, later vice-president, invited Behrend to give his engineering co-operation in modernizing the heavy products of the company, other than traction. The connection so formed continued when some two

years later Behrend found it necessary, on the score of health, to move to Boston. The plate rotor for turbo-generators was one of the outstanding developments introduced by Behrend at Pittsburgh. A littérateur, a brilliant engineer, a critical philosopher, Behrend also had those traits—failings as well as merits—which, by humanizing, endear a man to a wide circle of acquaintances. Always alert in cases of injustice, he became one of the most vigorous champions of Oliver Heaviside, and, indeed, was chosen as the intermediary for conveying the Honorary Membership awarded by the American Institute of Electrical Engineers in 1918. Upon Heaviside's death in February 1925, Behrend learned that his library was becoming scattered, and instructed his London booksellers to buy what they could of it. His intention was to present the collection to the British public, provided that he could find some custodian who would suitably value the heirloom, and up to within a year of his death he was much exercised in mind as to the most suitable destination from this point of view. He was a member of a large number of professional and scientific societies in America and Europe and the recipient of many medals and other honours, including the honorary degree of Doctor of Engineering conferred by the University of Darmstadt in 1931. His later years were enriched by his marriage in 1926 to Miss Margaret P. Chase of Boston, who survives him. He was elected a Member of the Institution in January 1932, only a few weeks before his death. A. B. F.

THOMAS BRITTEN died on the 16th March, 1932, at the age of 58. He was educated at Bedford School and spent four years as a pupil with Messrs. Robey and Co., of Lincoln, afterwards serving for a year as a draughtsman with the same firm. From 1895 to 1896 he was in the employ of Messrs. Ruston, Proctor, and Co. He then joined the technical staff of the Electric Construction Co. and remained with the firm until 1913. After obtaining some experience in the armature shop and on the test-bed, he took charge of the company's contract with the Bath Corporation for the installation of an electric lighting system. In 1899 he was made responsible for the execution of all the company's contracts in the London district, one of the more important of these being for the electrical equipment of the City and South London Railway. After being appointed general superintending engineer in 1902, his energies were chiefly devoted to the preparation and carrying-out of schemes for the electrification of large works. He was also responsible for the design and erection of the Park Royal and Royal Oak generating stations of the Great Western Railway, and a 15 000-kW lighting and traction plant for the Leeds Corporation, as well as for many other important contracts. Resigning his position with the Electric Construction Co., he was appointed works manager of Messrs. Crompton and Co. when the firm was reorganized in 1913. He subsequently became also a director of the company and served in this capacity up to the time of his death, although he retired from the position of works manager in 1927. He was also chairman of the Suffolk Iron Foundry, Ltd., and a director of the Hydraulic Engineering Co., and of various smaller concerns. As an engineer he was highly respected, and his advice was always regarded as valuable. He had a genial disposition, but was a man of very few words. He was elected a Member of the Institution in 1912. L. T.

JOSEPH NORMAN BULKLEY was born at Memphis, Tennessee, on the 17th September, 1867. He received his technical education at the Massachusetts Institute of Technology, from which he graduated in 1889. After a few months as a draughtsman with the Wright Engineering Co., of Boston, he accepted an appointment as engineer in the mining department of the General Electric Co. at Schenectady, and from 1890 to 1898 was engaged in designing and supervising the erection of electric coal-cutting machinery and other plant for use in mines. He was also in charge of the company's operations in the Pennsylvania district. Resigning his appointment in 1898, he went to South Africa to become chief engineer of the United Engineering Co., Johannesburg, where he was engaged for five years in directing the design and installation of electrical plant for a number of mining companies. In 1903 he became consulting engineer to the General Mining and Finance Corporation, in which capacity he had charge of the electrical equipment of all the mines controlled by that concern and was responsible for laying out all new plant. From 1909 onwards he was engaged in general consulting practice in London and New York, and returned to South Africa in 1922 to act as consulting engineer to the African and European Investment Co., Messrs. Guest, Sykes, and Chapman, Ltd., the Manganese Corporation, and other Johannesburg firms. He died at Gwelo, Rhodesia, on the 6th October, 1931. He was elected an Associate Member of the Institution in 1903, and became a Member the same year.

WILLIAM ARTHUR COULSON died at Kilmalcolm, near Glasgow, on the 22nd August, 1932. He studied electricity at the Hanover Square School of Electrical Engineering, and in 1886 entered into partnership with Mr. H. A. Mavor, who had been engaged in general electrical engineering work in Glasgow since 1881. The firm was first registered as a limited company in 1888, under the name of Muir, Mavor, and Coulson, Mr. Coulson taking charge of the financial side. In 1897 the size of the business warranted the issue of further share capital, and a new company was floated with the title of Mavor and Coulson, Ltd. Mr. Coulson remained a joint managing director of the concern from 1897 until his retirement a few years ago. He was for more than 20 years associated with Mr. F. G. Creed in the manufacture of telegraph apparatus, and in 1930 was appointed chairman of Messrs. Creed and Co. His kindness and courtesy won for him the affection of a wide circle of friends, although a retiring disposition kept his name from public notice. He was elected an Associate of the Institution in 1886, and a Member in 1891. S. M.

JOHN DENHAM was born in London on the 16th September, 1863, and died at Douglas, Isle of Man, on the 31st December, 1931. He obtained his training in electrical engineering at the Finsbury Technical College, and in 1881 became a pupil with the firm

of Latimer Clark, Muirhead, and Co. During his period of pupilage he took part in research work on the improvement of the electric arc lamp. In 1883 he entered the service of the Anglo-American Brush Electric Light Corporation, and undertook the installation of numerous electrical plants both in England and on the Continent. In 1888 his company placed him in charge of the erection and maintenance of the electrical equipment at the Brussels Exhibition. The following year he went to South Africa as electrical engineer to the Cape Government Railways, and in 1902 took up the additional appointment of electrical adviser to the Treasury. During the Boer War, and for two years afterwards, he acted as electrical consultant to the Royal Engineers. He became engineer in charge of the electrical equipment at the harbours of Cape Town, Port Elizabeth, and East London, when these were brought under the control of the Government Railways in 1909. He resigned his railway appointment in 1911, when he went to Johannesburg as government inspector of mines. On his retirement from that position in 1923 he returned to London. He was elected an Associate of the Institution in 1891, and a Member in 1897. He served for a time as Local Hon. Secretary and Treasurer for the Cape, Natal, and Rhodesia, and also as Chairman of the Cape Town Local Section.

BERNARD MERVYN DRAKE was born at Malta in 1858 and died on the 5th October, 1931, in his 74th year. He was educated at Rossall School and, after serving as a pupil in Sir Joseph Whitworth's works at Manchester and Gorton, entered, in 1881, the service of the Anglo-American Brush Co. While in their employ he carried out the lighting of the Buen Retiro in Madrid, the first premises in Spain to be lighted with incandescent lamps. He was afterwards appointed engineer to both the Great Western and the Brush Midland sub-companies, and had charge of the earliest power stations at Bristol, Cardiff, and Cleethorpes. In 1884 he was appointed managing director of the Electrical Power Storage Co. and had to solve many problems in connection with the manufacture and use of accumulators. These problems formed the subject of a paper before the British Association in 1886. In that year he went into partnership with the late John Marshall Gorham and founded the firm of Drake and Gorham, of which he afterwards became chairman and managing director. The firm became actively engaged in installing electric generating plants and wiring throughout the country, and contracted for many of the best-known country residences. He was instrumental in putting on the market many useful inventions, such as the Cardew earthing device and the hot-wire voltmeter, and he and Mr. Gorham were the patentees of the spring-contact switch which was used as a standard for many years. He was associated with the development of the Jandus arc lamp and was chairman of the Nernst lamp company until that invention was superseded by the metal-filament lamp. He held the position of consulting engineer to the Bank of England for 25 years and was personally responsible for the large installations at the Prudential Assurance Co., Chatsworth, Alnwick Castle, Crewe Hall, etc. In 1895, in conjunction with Messrs. Gorham and Claude Johnson, he founded the D.P. Battery Co., and later became chairman of the Tudor Accumulator Co. and also of the National Accumulator Co. He was elected an Associate of the Institution in 1883 and a Member in 1886, and served on the Council in 1902–5. At the Commemoration Meetings in 1922 he contributed a paper (see vol. 60) on "Recollections of Early Electrical Engineering." He was for over 36 years a member of the Institution's Wiring Regulations Committee, and was also a member of the Electrical Trades Committee which was appointed by the Board of Trade to report on Trade after the War. As a tariff reformer he had consistently advocated the protection of home trade from foreign competition. He had a striking presence and personality, was undoubtedly one of the small band of influential pioneers who helped to bring the electrical industry to its present outstanding position, and he was invariably associated with any new development. In addition to his many business interests he was a very keen fly fisherman and an excellent game and rifle shot. The writer of this notice was personally acquainted with him since 1888, and greatly esteemed his upright, independent, and sterling character.

S. G. C. R.

CHARLES LEAVITT EDGAR, president and general manager of the Edison Electric Illuminating Co., of Boston, Massachusetts, died on the 14th April, 1932, at Atlantic City, New Jersey, at the age of 71. He received his technical education at Rutgers College, New Brunswick, and graduated in 1882. Leaving the college the same year, he was appointed to the staff of the Edison Electric Light Co. as superintendent of the test room at the New York factory, and was promoted in 1884 to the position of assistant engineer in charge of the company's contracts for the erection of central stations. Shortly after his appointment in 1887 as chief engineer of the company, he was transferred to the position of general superintendent of the newly-formed Edison Electric Illuminating Co. of Boston. He saw 45 years' service with this concern, of which he was made general manager in 1889, vice-president in 1894, and president in 1899. He made several trips to Europe in order to study the methods of Continental supply engineers, and as a result of these investigations he introduced into America the use of storage batteries as central station auxiliaries. He also foresaw the importance of compact generating units for stations in congested districts, and installed at Boston the first vertical engines used in America for central station work. On a special visit to England in 1898 he studied the Wright demand system of charging, which was subsequently adopted at Boston. Throughout his life he was a keen student of sociology, and devoted much of his leisure to welfare work among the employees of his company. In 1927 Rutgers College conferred upon him the honorary degree of D.Sc. He was elected a Member of the Institution in 1905.

THOMAS ALVA EDISON, who died on the 18th October, 1931, enjoyed a world-wide reputation as a scientific inventor which has probably never been rivalled. The following statement gives no more than the bare facts

of his wonderful career. He was born at Milan, Ohio, on the 11th February, 1847. He was educated by his mother until, while still a boy, he obtained permission from the authorities to sell newspapers on the Grand Trunk Railway trains. His natural interest in science was stimulated by daily contact with railway engines and the electric telegraph, and he spent the bulk of his earnings on books and scientific apparatus. In his leisure he found time to master the subject of telegraphy, and in 1863 he became a telegraph operator on the Grand Trunk Railway. The following year he joined the Western Union Telegraph Co., and later spent some time in their office at Boston. Here he bought a complete set of the works of Faraday and began to make experiments in electromagnetism. He was granted his first patent in 1869, for an electric vote recorder, but his efforts to get the device installed in the House of Representatives proved fruitless. He therefore determined to devote himself in future to inventions for which there was likely to be a demand. Resigning his post at Boston, he went to New York, where his technical knowledge soon gained him the position of manager of the Gold Indicator Co.'s telegraph plant for informing stockbrokers of prices on the Gold Exchange. The improvements which he made to the system then in use attracted the attention of the Western Union Co., at whose request he undertook experiments with a view to improving their " stock-ticker " instrument—the forerunner of the tape machine. The results of these experiments were embodied in the Edison universal printer, the patent rights of which he sold for $40 000. Thenceforward he was assured of financial independence, and was free to devote himself to his career as an inventor. In 1870 he came to England for the Automatic Telegraph Co., in order to demonstrate their automatic system to the telegraph officials of the British Post Office. He next turned his attention to telephony, and by making use of a carbon microphone in conjunction with an induction coil he evolved the first transmitter which could be used over long-distance lines. In 1879 he produced his loud-speaking telephone and sent representatives to introduce it into Great Britain, where it achieved some measure of success. Edison's pet invention, the phonograph, originated in 1877 as the result of some experiments with the automatic telegraph. The popularity of the early type of instrument, in which the record was made on tin-foil, was short-lived; but in 1887 he greatly improved upon it by substituting wax as the recording medium, and in this form the instrument was a commercial success. He also developed an ingenious electrical method for making copies of existing records. In 1877 he made his preliminary experiments on electric lighting. He passed an electric current through carbon strips in air, and found that when heated to incandescence they at once became oxidized and crumbled to pieces. When placed in as good a vacuum as was obtainable with a common air-pump, however, the carbon strips remained intact for 10 to 15 minutes before they burnt out. Platinum and iridium wires were then tried, but it was found that the current required to produce incandescence was sufficient to melt them within a short time. The next step was to use a mercury vacuum pump and to heat the filament to incandescence while the bulb was being evacuated, in order to remove occluded oxygen. Finally, after much patient research work, a carbon filament was produced which could be maintained at a higher temperature than platinum wire and was more efficient as a light source. The filaments of the first electric lamps were made from carbonized cotton thread, but before manufacture could be begun on a large scale a more durable material had to be discovered. After exhaustive tests Edison hit upon the idea of using carbonized bamboo fibres, which he considered to be superior to all others for the purpose. During the course of these investigations he discovered the " Edison effect," later to be used by Fleming and Wehnelt as the principle of their rectifiers, and ultimately developing into the many forms of thermionic amplifying valves now in use. While the work on the incandescent lamp was still going on, Edison was engaged in planning his system of electric lighting and in improving the dynamo. He made use of a laminated armature core, insulated the commutator with mica, and increased the amount of iron in the field magnets. He also realized the advantage of using a high-speed steam engine direct-coupled to a single large generator unit. In 1880 he floated the Edison Electric Illuminating Co. of New York, which proposed to give a public supply of electricity by the newly developed feeder-and-main method of distribution, the energy being measured by the Edison electrolytic-type meter. The Edison system was adopted in the world's first central-station electric lighting plant, which was put into operation on Holborn Viaduct in 1882 and remained in continuous use for many years. The greater part of Edison's later life was spent in inventing improvements on existing appliances. He patented early forms of cinema cameras and projection lanterns, and evolved a new process for the reduction of magnetic iron ores. In 1909 he began to manufacture a nickel-iron storage battery having an alkaline electrolyte, the product of about 10 years' research work by himself and a selected staff. He was elected a Member of the Institution in 1911, and an Honorary Member in 1927.

MAX KAI ESSKILDSEN was born in Copenhagen on the 18th June, 1858, and died during a visit there on the 9th September, 1931. In 1878 he was appointed a probationer at the Great Northern Telegraph Co.'s Newcastle station, the following year attaining permanent employment. After a short stay in London, he was, in 1881, transferred to Nystad in Finland, where he spent 5 years, after which he returned to London, where he was destined to remain for the rest of his days. Having, in 1888, passed an electrical course, he regularly assisted at the cable factories, which particular work he continued after having, in 1894, been transferred to the engineering department of the London office. Here he gradually rose through all the grades, being appointed head of the department in 1905. He furthermore acted as joint manager of the London office, from 1919 until 1923, when he was pensioned. This, however, did not mean complete retirement from work, as, until his death, he remained at the company's disposal for weekly consultations. He joined the Institution as an Associate in 1890, and became a Member in 1915.

In 1919, he was made a " Knight of Dannebrog " by the King of Denmark.

FREDERICK WILLIAM GEOGHEGAN died on the 3rd May, 1932, at the age of 48. Educated at preparatory schools in Ireland and later at Shrewsbury School, he was apprenticed in 1902 to Messrs. C. A. Parsons and Co. In 1905 he spent 6 months as a pupil at the generating station of the Cambridge Electric Supply Co., and then entered upon a 3-year course in electrical engineering at the Central Technical College, South Kensington. His first appointment was that of electrical engineer to Messrs. J. Summers and Sons, Stalybridge, for whom he superintended the erection of switchboards and induction motors. In 1909 he entered the service of the British Columbia Electric Railway Co. as an outside inspector. He then spent a few months in the armature-winding shops of the Canadian Westinghouse Co. and towards the end of 1910 secured a position in the office of the city engineer at Prince Rupert, British Columbia, assisting in the erection of the machinery at the new municipal power station. He returned to Ireland in 1912 as a director and partner in the Dublin Marine Motor and Boat Co. In September 1914 he joined the Royal Naval Volunteer Reserve with the rank of lieutenant, and took part in mine-laying operations. In 1918 he was promoted to the rank of lieutenant-commander. After the War he joined the Castner-Kellner Alkali Co., Runcorn, where he was employed as shift engineer. Resigning this appointment in 1920, he rejoined Messrs. Parsons as superintending engineer in connection with electrical repair work, and was sent out to South America to supervise some alterations to the turbo-alternator plant of the Central Argentine Railways. For the greater part of 1921 he was attached to the firm's London office, and in December of that year went to Australia as engineer in charge of the company's contracts for the erection of turbo-alternators at the Newport (Melbourne) power station of the Victorian Railway Commissioners and the Perth power station. He was subsequently stationed at Melbourne as Messrs. Parsons' resident engineer in Australia, a position which he filled until his return to England in August 1929. He was elected a Student of the Institution in 1908, an Associate Member in 1910, and a Member in 1926.

PROFESSOR WILLIAM GRAHAM GRIFFITH, B.Sc. (Eng.), was born at Barbados in 1879, and received his early education at Harrison's College in that island. He came to England in 1896 and received his professional training at the Heriot Watt College, Edinburgh. He then served his apprenticeship with Messrs. Mavor and Coulson and took a B.Sc. degree in Engineering as an external candidate of London University. He was a lecturer in electrical engineering under Prof. Baily at his old college from 1903 to 1905, when he obtained a position as engineer with Messrs. Siemens Brothers, specializing in the design of transformers and electrical machinery. He first went to Ireland in 1907 temporarily for six months, and in September of that year was appointed lecturer at the Bradford Technical College, where he remained until the following January when he was asked to return to Galway as lecturer. When, later, a chair of electrical engineering was founded he was appointed to it, and at once proceeded to develop his department and to establish a laboratory. The laboratory which he equipped in Galway is one of the best small laboratories in Ireland and much of the fitting up was done with his own hands. He was an enthusiast in his subject and did wonders with the limited resources at his command. At that time the college attracted a large number of students, not only from what is now the Irish Free State but also from Northern Ireland. At the outbreak of war he at once volunteered for service but was rejected on medical grounds; he remained at his post, but without any assistance. He carried the burden of the electrical engineering department single-handed for many years, and even after the War, when the number of students began to increase once more, he had himself to conduct the full degree course in electrical engineering. The standard which his students reached was evidence of the skill and thoroughness of his teaching; and many of his former students are among the most distinguished electrical engineers in Ireland and elsewhere. He was a genial and interesting companion, a man of wide reading and literary appreciation, a keen trout angler, and very fond of sailing and camping on the banks of Loch Corrib. His death, which occurred on the 10th January, 1932, was a great loss to electrical enginering in Ireland, where he was widely known and esteemed. He was elected an Associate Member of the Institution in 1906 and a Member in 1928. E. W. M.

CECIL WILBERFORCE GWYTHER was born in England in 1867 and was educated in the Old Wallasey Grammar School. In 1884 he entered the service of the United Telephone Co. in London, who were the holders of the Edison Bell patents for telephones. In this company he occupied a position in the departments for the construction of telephone exchanges. In 1886 he joined the Lancashire and Cheshire Telephone Co. in Liverpool and was in charge of the construction of exchanges. While there, he assisted in the installation of the first multiple telephone switchboard and also the installation of the first paper- and lead-covered telephone cables. In 1892 he was promoted to the post of local manager of the Chester and North Wales district of the National Telephone Co., and in 1893 was made district manager of the same region. In 1895 he was transferred to Dublin as manager, at the same time as Mr. Frank Gill became superintendent for the whole of Ireland. In 1900 he left for Buenos Aires to enter the service of the United River Plate Telephone Co. as constructional engineer, and in 1903 he was promoted to chief engineer and in 1906 sub-technical manager. Eventually he was appointed technical manager, which position he held in August 1905 when he retired after 23 years' service with the Union Telefonica, the name by which the River Plate Co. was known in Argentina. He died on the 13th December, 1931. He was a man of high culture and a retiring disposition. He was elected an Associate of the Institution in 1894 and a Member in 1898.

F. W. R.

WILLIAM JOHN HANCOCK, D.Sc., who was born in Dublin on the 2nd May, 1863, and died on the 26th August, 1931, was educated at the University of Glasgow. He joined the Telephone Co. of Ireland in 1882, and three years later was appointed to the Government service of Western Australia, where he became superintendent of Government telephones and subsequently Government electrical engineer. In his work of extending the telephone system he had to contend with many difficulties peculiar to the country. He supervised the erection of the majority of the generating stations now at work in Western Australia and also designed and installed the electrical equipment of Fremantle and Bunbury harbours. He also undertook a wide variety of engineering work, ranging from investigations into the problem of electrolysis in water mains to the designing and erection of a new type of control for time-ball signals. In addition, he was for many years Government inspector of tramways. His active interest in radiology began in 1896. After making some preliminary experiments with his own X-ray tubes he offered his services to the medical department, with the result that he was appointed honorary radiographer to the Perth Hospital, where he worked for 22 years. He devoted the greater part of his spare time to this public service, which cost him the use of the fingers of both hands and was ultimately the cause of his death. For many years he was a member of the senate of the University of Western Australia, which conferred upon him the honorary degree of D.Sc., and he was also awarded the Kelvin Medal of the Royal Society of Western Australia. He was elected a Student of the Institution in 1882, an Associate in 1884, and a Member in 1889; and he served as Local Honorary Secretary for Western Australia from 1888 to 1926.

ALFRED HANDS, chairman of Messrs. J. W. Gray and Son, Ltd., died at Hockley, Essex, on the 10th October, 1932, at the age of 73. Throughout the greater part of his life he specialized in protection against lightning, and he was the author of a number of publications dealing with that subject. He also delivered many lectures on the subject. From 1889 to 1891 he was in business as Messrs. A. Hands and Co. He then became a partner in the firm of Messrs. J. W. Gray and Son, and remained with them until his death. Among the numerous buildings for which he was responsible as regards their protection against lightning were Sandringham House, the Houses of Parliament, Osborne House, the Guildhall, and St. Paul's Cathedral. He was elected a Member of the Institution in 1910.

GENERAL SIR RICHARD HARRISON, G.C.B., C.M.G., R.E., died on the 25th September, 1931, at Brixham, Devon, aged 94 years. Born in 1837, he was educated at Harrow, and obtained his military training at Woolwich Arsenal. He was granted a commission in the Royal Engineers in 1855, and a few months afterwards was sent out to take part in the Crimean War. Hostilities had already ceased before he reached his destination, however, and he was recalled. The following year he sailed for India to join the forces engaged in the suppression of the Mutiny, and took part in the ultimate capture of Lucknow. His next campaign was with Sir Hope Grant's expedition to China, where his prowess at the siege and capture of Taku Forts in 1859 earned him the rank of brevet major. On his return to England he was stationed at Aldershot with the rank of brevet lieutenant-colonel. In 1877 he gained the Royal Engineers gold medal for an essay dealing with the applications of engineering to warfare. On his return from a successful campaign against the Zulus in South Africa, he was appointed C.R.E. at Aldershot in 1880, and soon after became A.Q.M.G. Two years later he was made A.A.G. to General Earle, who had been selected to command the communications in the forthcoming Egyptian expedition. Colonel Harrison was at this time chairman of a committee which had been appointed to reorganize the military telegraphs of the British Army. In 1884 he went out to Egypt with Lord Wolseley's force in an attempt to relieve General Gordon, but while in charge of the line of communications beyond Wady Halfa he was invalided home. His first general officer's appointment came in 1889, when he was made Governor of the Royal Military Academy. The following year he was placed in command of the Royal Engineers in the Western district, and was stationed at Devonport in this capacity until 1895, when he was promoted to the rank of general. In 1898 he was appointed Inspector-General of Fortifications and member of the joint Naval and Military Committee of Defence, and after five years' tenure of this office he retired, having completed 49 years' army service. He was created C.B. in 1879, C.M.G. in 1882, K.C.B. in 1889, and G.C.B. in 1903. He was elected a Member of the Institution in 1882.

ALFRED HAY, D.Sc., who died on the 13th April, 1932, was born of Scottish parents at Warsaw, Poland, on the 3rd April, 1866, and received his early education at one of the Warsaw "Gymnasia." He served his apprenticeship as an electrical engineer with Messrs. McWhirter, Ferguson, and Co., of Glasgow, and began his theoretical training at the Glasgow and West of Scotland Technical College. From 1888 onwards he attended classes in electrical technology at Edinburgh University, where he took the degree of B.Sc. with first-class honours in 1891. At one period of his career at Edinburgh he conducted classes at the Heriot-Watt College. After graduating, he studied for two terms at the Central Technical College, South Kensington, and was then appointed demonstrator in electrical engineering at University College, Nottingham. During his four years' tenure of this post he carried out some research work into the nature of the current-rushes which occur when a transformer is switched on to live mains. He also investigated the oscillatory currents which occur under certain conditions when a condenser is charged or discharged. In 1896 he became lecturer in electrotechnics at the University of Liverpool, and remained there until 1901, the year in which Edinburgh University conferred upon him the degree of D.Sc. Among the researches which he carried out at Liverpool was an experimental investigation of the streamline method of solving magnetic problems, in which he collaborated with Prof. Hele-Shaw. From 1901 to 1903 he occupied

the chair of electrotechnology at the Royal Indian Engineering College, Coopers Hill, where he also lectured as a visiting professor until 1908. In 1903 he was appointed to the position of head of the physics and electrical engineering department at the Hackney Technical Institute, a post which he filled until the close of 1907. In January 1908 he went out to India as professor of electrical technology at the then newly-established Indian Institute of Science, Bangalore. On his retirement from this position in 1923 he returned to England. Besides contributing widely to the technical Press, he was the author of a number of books on electrical engineering subjects. He was elected an Associate of the Institution in 1887, and a Member in 1900.

CHARLES HENRI JULIUS, a director of Messrs. J. G. White and Co., died on the 15th December, 1931, at the age of 59. He was educated at the Naval Academy, Helder, Holland, and the Institut Montefiore, University of Liége, where he took his degree in 1894 and gained the "Prix Montefiore." After spending a year as a pupil with the Société Anonyme Électricité et Hydraulique, of Charleroi, Belgium, he accepted an appointment as electrical engineer with the same company, in whose employ he remained until 1899. Among other work in which he took part during this period was the construction of one of the first electric tramways in Belgium, that from Liége to Cointe. He subsequently went to Russia and South America in order to investigate plans for new tramway systems to be laid down by his company. In 1896 he was sent to make a report on the proposed hydro-electric developments in Java, and the following year he became resident engineer in charge of the construction of a tramway system in North Africa, linking up Algiers, Mustapha, and Maison Carée. Resigning his appointment with the Charleroi company, he went to Russia in 1899 as general manager of the St. Petersburg Electric Lighting Co., but returned in 1900 to take up tramway work in Paris as chief engineer of the Compagnie Générale de Traction. During his stay of two years with this company he laid down about 20 miles of tramways in Paris and its suburbs, and directed the development of the Diatto system. From 1902 to 1904 he was electrical engineer to the Société Anonyme Westinghouse at Havre, where among other work he had charge of the company's contract for the construction of the Cintra tramway system, Portugal. He returned to his native country, Holland, in 1904, and spent the following eight years as managing director of the Haarlem–Amsterdam Electric Railway Co. In 1912 he came to London to take up an appointment with Messrs. J. G. White and Co., with whom he remained up to the time of his death. He was made a director of the company in 1917. His work was chiefly concerned with the management of tramway and lighting properties in South America on behalf of the firm. He was elected a Member of the Institution in 1918.

JAMES WILLIAM KEEFE, assistant technical director of Standard Telephones and Cables, Ltd., died on the 6th July, 1932, aged 51 years. After being educated privately, he took a 2-year course in electrical engineering at Finsbury Technical College from 1896 to 1898. The following year he joined the Western Electric Co. (now Standard Telephones and Cables, Ltd.) and thus entered upon what was to be a career of 33 years of work devoted to the telephone industry. After a short period in the cable testing department of the company he was transferred in January 1900 to the telephone department, and assisted during the installation at Bristol of the first C.B. exchange opened for public service in England. In May, 1900, he was engaged on construction work for the Post Office London telephone system, and assisted in the erection of various exchanges, the first of which was known as "Central" and was situated in Savings Bank Buildings, Carter-lane. He was appointed chief installer in 1903, and shortly afterwards left England to install C.B. exchanges in Lisbon and Durban. With 1909 came his appointment as manager of the South African branch office at Johannesburg, a position which he retained until October 1922. His invariable geniality and good humour, and his inexhaustible stock of stories and reminiscences, endeared him to a large circle of friends in South Africa. He returned to London in October 1922 to take up duties in the sales department, and was appointed assistant sales manager in charge of the equipment division in 1924. During this period the growth of the company's Continental business, especially in the repeater and loading-coil fields, made it necessary for him to visit many Continental centres, and in September 1927 he was transferred to the European commercial department of the International Standard Electric Corporation, to enable him to devote the whole of his energies to this phase of the business. November 1929 found him back again with Standard Telephones and Cables, Ltd., as sales manager. Unfortunately his health broke down shortly afterwards, and he was given the rather less worrying position of assistant technical director. In the limited amount of leisure he allowed himself he followed various hobbies, chief of which was probably his interest in books, of which he was an omnivorous reader. He was elected a Member of the Institution in 1921.

F. K. J.

FREDERICK WILLIAM ANTHONY KNIGHT died at his home in Guernsey on the 12th October, 1932, at the age of 68. After being educated at private schools he became in 1884 articled to the late Sir Charles Bright, with whom he remained until 1887. He was then appointed to the submarine staff of the India Rubber, Gutta Percha, and Telegraph Works Co., and took part in cable-laying expeditions to the west coast of Africa and the west coast of South America in the C.S. "Silvertown." In November 1894 he was transferred to the Western and Brazilian Telegraph Co. as chief electrician of the C.S. "Norseman," with headquarters at Pernambuco, Brazil. There he remained until his retirement in 1919, when he settled down in Guernsey. He was elected a Student of the Institution in 1885, an Associate in 1887, an Associate Member in 1899, and a Member in 1901.

H. S. J. K.

CYPRIEN ODILON MAILLOUX died in New York on the 4th October, 1932, at the age of 74. After a varied education, in the course of which he studied

foreign languages, classics, medicine, and science, he became in 1882 the first editor of the *Electrical World*. He resigned that position in 1884 and set up as a consulting electrical engineer, in which capacity he was subsequently responsible for the design and erection of several central stations and numerous private generating plants both in the United States and elsewhere. He took a great interest in the work of the International Electrotechnical Commission and attended practically every meeting of the Commission from its inception up to the time of his death, and he was elected president in 1919. In 1916 he came to Europe as a representative of the United States Government on the Commission appointed to report on research in the industrial and scientific branches of electrical engineering. He was elected a Member of the Institution in 1901.

JOHN MAY died on the 2nd September, 1932, at the age of 66. After spending three years as a pupil at Rugby School, he entered University College, London, in 1882, and studied engineering for three years. From 1885 to 1889 he was articled to Messrs. Easton and Anderson, of Erith, and towards the end of this period was sent by the firm to assist in the erection of machinery at the Amsterdam waterworks. He subsequently spent three years at Newcastle-on-Tyne in the drawing office of Messrs. Ernest Scott and Mountain. On his return to London in 1892 he studied for a short time at Faraday House before taking up an appointment as assistant to the late Mr. Robert Hammond. In this capacity he was associated with the design and erection of many large generating stations, including those at Leeds, Hackney, and Dublin. The Dublin plant was the first in the British Isles to give a 3-phase public electricity supply, and its installation involved a change of frequency in addition to the amalgamation of the old single-phase system with the new scheme. After about 14 years he resigned his position under Mr. Hammond and set up in business as a consulting engineer in partnership with Mr. G. W. Spencer Hawes. His success as a consultant was appreciated only by those who knew him well, for he was of a modest and retiring nature. He was elected an Associate of the Institution in 1892, and a Member in 1901.

FRANCIS JOSEPH MOFFETT was born in 1869 and died at Birmingham on the 9th December, 1931. His technical education was obtained at the School of Electrical Engineering, Hanover Square, London. On the completion of his course, he obtained the B.A. degree of London University. After an engineering apprenticeship, he was employed by the National Telephone Co., and the Woolwich Electricity Supply Co. His next appointment was that of chief electrical engineer to Southern Nigeria, where he superintended the erection of the Lagos power station. Later he joined the staff of Messrs. Preece and Cardew, in connection with the electrical equipment of H.M. dockyards and other schemes. It was in this connection that he met Mr. N. B. Rosher, who was engaged on similar work. In 1908 he set up in partnership with Mr. Rosher in Birmingham as a consulting engineer. The partnership continued until 1921, when Mr. Rosher retired from the firm. During this period the firm was advising upon and carrying out electrical schemes, chiefly in connection with the industrial uses of electricity. Upon Mr. Rosher's retirement, Mr. Moffett took Mr. F. H. Mann into partnership, but at the time of his death he was the sole partner in the firm of Moffett, Rosher, and Mann. He was elected an Associate of the Institution in 1891, an Associate Member in 1903, and a Member in 1908; and was Chairman of the South Midland Centre in 1925–26. His address as chairman was on the subject of "Imagination in Engineering" and was one of the ablest addresses delivered to that Centre. He was a man of strong character, keen intellect, and wide interests. He had no patience with duplicity or pettiness in any form. He was held in high esteem by a very wide circle of engineers in the Midlands, and by a much wider circle of laymen, on account of those qualities which are admired by all—courage to say and do the right thing, ability, and a warm heart.

WILLIAM BOWMAN PACKHAM was born in 1877 at Dundee, and received his technical education partly at Dundee University and partly at Liverpool University. He served his apprenticeship with Messrs. Gourlay Brothers and Co., shipbuilders, of Dundee, and then obtained four years' marine experience with the Bedouin Line of Liverpool. He received a commission in the Royal Naval Reserve, but resigned it in order to take up electrical engineering. In 1902 he entered the Preston works of Messrs. Dick, Kerr, and Co., and worked as a draughtsman and in the electrical testing department. In 1904 he joined the Lancashire and Yorkshire Railway Co. as power station superintendent at Formby in connection with the company's electrified section from Liverpool to Southport. In 1908 he was appointed operating and works engineer by the Calcutta Tramways Co., and remained with them until 1922. In 1923 he returned to England to take charge of the West Gloucestershire Power Co.'s Lydney station, and held that position until the onset of the illness which ended in his death on the 24th April, 1931. He was elected an Associate Member of the Institution in 1908, and a Member in 1920.

JAMES HENRY SHAW was born in Belfast on the 20th August, 1876. He entered the service of the Post Office as a telegraphist in 1892 and worked for some five or six years in the Belfast instrument room. From the outset of his official career he took the deepest interest in technical matters, and after a brief period on clerical duties in the engineering department he was appointed sub-engineer in 1899. His early engineering service was in Dundee, whence he transferred to Tralee. Here, and later on at Cork, he took a considerable part in the work—then just beginning—of the telephoning of Ireland, a work in which he displayed the keenest interest throughout his career. Indeed, it is not too much to say that the network of telephone lines now extending to even the most sparsely populated parts of Ireland is largely a monument to his energy and zeal. When the negotiations for the purchase of the property of the National Telephone Co. by the State were in progress he was appointed to the Post Office inventory

staff, and in this capacity travelled over a wide area of the British Isles. While the inventory was still in progress he was appointed executive engineer at Athlone. Later his headquarters were changed to Dublin, and for some years before the setting up of the Irish Free State he was on the headquarters staff of the superintending engineer, Dublin. At the change of Government he elected to serve under the new administration and was a staff engineer in the engineering branch of the Department of Posts and Telegraphs at the time of his death. Somewhat aloof and reserved to the stranger, he had the gift of winning the esteem and affection of those who really knew him, and he was always unsparing in his efforts to help his colleagues to solve their problems, technical and personal. He was elected a Member of the Institution in 1921 and was very active in the interests of the Irish Centre, of which he was Chairman in 1925–26. He died on the 25th January, 1932. T. J. M.

HAROLD BABBITT SMITH was born on the 23rd May, 1869, and died on the 9th February, 1932. Educated at the Barre Academy, Massachusetts, and Cornell University, he was in 1892 appointed professor of electrical engineering at the University of Arkansas. After a year's service he resigned this appointment in order to become consulting engineer and designer to the Elektron Manufacturing Co., Springfield, Massachusetts, where until 1901 he was in charge of the company's design and development work in connection with the manufacture of motors, generators, and electric elevators. From 1893 to 1896 he held in addition the post of director of the electrical engineering department at Purdue University. In July 1896 he was appointed the first professor and head of the newly-established department of electrical engineering at the Worcester Polytechnic Institute, Massachusetts, a position which he held up to the time of his retirement in 1931. He also acted from 1905 as consulting engineer to the Westinghouse Electric and Manufacturing Co. and carried out for them an important series of investigations into dielectric phenomena and stress distribution problems at extremely high voltages. From 1917 to 1919 he was a member of the special board appointed by the United States Navy to assist in the development of anti-submarine devices, and he was placed in charge of naval research work at New London. In 1929 Purdue University and the Worcester Polytechnic Institute both conferred upon him the honorary degree of Doctor of Engineering. He was elected a Member of the Institution in 1903, resigned in 1921, and was re-elected a Member in 1927.

HORACE MORTON TAYLOR died on the 21st December, 1931, at the age of 59. He received his early education at Aldenham School and his technical education at the School of Electrical Engineering, Hanover Square, London. After serving his apprenticeship with Messrs. John Fowler and Co., he obtained a post with the Eastbourne Electric Light Co., and subsequently became mains engineer to the West Brompton House-to-House Co. In 1895 he joined the staff of the late Mr. Robert Hammond, and later was for a short time chief assistant to the borough electrical engineer of Newport, Monmouthshire. In 1900 he received an appointment with the British Westinghouse Co. and was responsible for the erection of the Chesterfield Corporation electric supply works. In 1902 he became borough electrical engineer at Middlesbrough and remained there until shortly after the outbreak of war, when he joined the Submarine Miners, a Corps attached to the Royal Marines. He was Captain in command at Landguard Fort, Felixstowe, for six months, and was then transferred to Inch Mickery, an island near the Forth Bridge. Later he was employed by the Admiralty as a resident director of research, and worked under Mr. Merz and Prof. Bragg at Wemyss Bay. On being demobilized in 1919 he helped ex-service men under the late General Haig, who wrote him a personal letter of thanks. In 1920 he was sent by the Government to Malaya, but was recalled soon afterwards owing to reductions in expenditure. From November 1922 up to the time of his death he was chief engineer and manager of the Llanelly and District Electric Supply Co. He was joint inventor of the Taylor and Scotson voltage regulator, and some of his Admiralty work was directed to the use of the induction loop in anti-submarine work. He also invented a light for use in locating submarines when submerged in clear water. He was elected a Member of the Institution in 1920. W. J. H. P.

CHARLES SHELDON THOMSON, who died at Wimbledon on the 18th May, 1932, was born at Altrincham, Cheshire, in October 1868. He was educated at Mill Hill School and Manchester University, where he took his B.Sc. degree and was awarded the Fairbairn Engineering Prize. Later he took his M.Sc. degree. He became a pupil at the works of the Brush Electrical Engineering Co. and later obtained an appointment with that company. After being with them for some years he joined the staff of the late Mr. Robert Hammond. He was subsequently appointed to the staff of the British Westinghouse Co., and left them to join the Electric Ordnance and Accessories Co., later becoming sales manager of the electrical department of Messrs. Vickers. In 1919 he was transferred to Metropolitan-Vickers Electrical Export Co., with whom he held an important position up to the time of his death. He was of a retiring disposition, but to his friends he was a most loyal comrade and his very sound advice and help on personal or engineering matters was highly valued by all who knew him. He was elected an Associate of the Institution in 1889, an Associate Member in 1899, and a Member in 1900. A. H. F.

ALFRED HENRY WALTON was born in 1862 and died in 1931 at the age of 68. He commenced his training in the engineering works of Messrs. Hayward, Tyler and Co., in 1876, and attended Finsbury Technical College until 1883. His practical work covered the whole period of electric lighting, beginning with drawings for the first plant in this country, the Holborn Viaduct installation of the Edison Electric Light Co. in 1880, and for that company's exhibit in the following year at the Crystal Palace Exhibition; also for the subsequent reconstruction of the Edison dynamos to the improved design known as Edison-Hopkinson. For the next four

years he was with the Telegraph Construction and Maintenance Co., working under the late Mr. J. E. H. Gordon on the design of the earliest 2-phase alternators, some being used for lighting their own shops and others for lighting Paddington Station, including also the steam-generating plant and the " divided mains " devised to meet the conditions of a contract to give constant voltage-loss at all loads, resulting in maximum economy during the maintenance period. He then joined the Great Western Railway Co.'s staff for three years, during which he improved the efficiency of the generating plant and installed electric light on the company's three steamers. From 1895 to 1898 he was engineer to the Metropolitan Electric Supply Co., having been chief assistant engineer for the previous 5 years. Towards the end of 1898 he joined the British Thomson-Houston Co. to take charge of their two contracts for electrification and two years' operation of the Central London Railway, and in July 1899 he was promoted to be chief engineer of the company. When the latter commenced to manufacture in England he was appointed manager for the London area and of the heavy traction department. He also served as technical adviser to the Chatham and the Lanarkshire traction companies, and was managing director of the Cork Electric Supply Co. He was keenly interested in fishing, sailing, and bowls. Consistent, fearless straightforwardness and absolute reliability, even if to his own detriment, were his outstanding, sterling qualities. He was elected a Member of the Institution in 1895, and served on the Council from 1909 to 1911.

T. S.

HENRY DANIEL WILKINSON died at his home at Streatham on the 24th February, 1932, in his 75th year. He was educated at Cowper Street School, London, and subsequently took a course of training in London and Cornwall for the submarine cable service. In 1875 he went out to the Straits Settlements as electrician to the Eastern Extension Telegraph Co., and spent the following 6 years at the company's stations at Singapore and Penang. He returned to England in 1881, and shortly afterwards became a tutor at the School of Electrical Engineering, Hanover Square, London. Resigning this appointment after a few years' service, he went as a mechanical engineer to Messrs. Davey, Paxman, and Co., and took part in the erection of engines and boilers for this firm at the Paris Exhibition of 1889. In 1891 he acted as mechanical and electrical engineer to the executive of the Royal Naval Exhibition, Chelsea. At the conclusion of the Crystal Palace Exhibition, where he represented Messrs. Davey, Paxman, and Co., he was in 1892 engaged, as assistant to Mr. W. H. Massey, in drawing up plans for the Cardiff electric lighting scheme. The following year he went to America as mechanical and electrical engineer to the British Royal Commission for the Chicago Exhibition, and subsequently made a detailed study of the tramway systems of the U.S.A. and Canada. This investigation formed the subject of a paper entitled " Notes on Electric Tramways in the United States and Canada " which he read before the Institution in 1894, and for which he was awarded the Institution Premium. His next post was that of superintending engineer to Messrs. Willans and Robinson, and shortly afterwards he accepted the appointment of station engineer in the service of the Westminster Electric Supply Corporation. In 1898 his advice was sought by the Eastern and South African Telegraph Co. in connection with the interference on their cables at Cape Town, due to neighbouring tramway circuits. He at once went to South Africa to investigate the trouble, and subsequently made similar investigations for the company at Durban and Pietermaritzburg, and acted in a consultative capacity for various electric tramway and power supply authorities. While he was in Cape Town the Boer War broke out and he joined the Civic Guard. On his return to England in 1902 he set up in practice as a consulting engineer, and did a good deal of work for the cable companies. He acted as consulting electrical engineer to Birmingham University, and was for many years an acknowledged expert on theatre lighting. At the beginning of 1932 he entered into partnership with Messrs. Mackness and Shipley, consulting engineers, of Victoria-street, London. He was a prolific writer on electrical subjects. He was elected an Associate of the Institution in 1876, and a Member in 1886.

PROFESSOR ERNEST WILSON was born on the 25th November, 1863, at Alford, Lincolnshire, where his father was a solicitor. His early education at Alford Grammar School, where he showed an enthusiasm for games which he retained for life, was followed by apprenticeship, in 1882, to Messrs. Greenwood and Batley, at whose works he took part in the building of some of the earliest Brush and Ferranti alternators. While an apprentice he attended evening classes at Yorkshire College and subsequently became a student-assistant in the day courses. The good use which he made of his opportunities was rewarded in 1886 when he received a Whitworth Scholarship. This enabled him to go to Germany where, at the Königlische Technische Hochschule, Hanover, he became a pupil of Prof. Kohlrausch and gained valuable experience in electrical testing and a thorough knowledge of the German language. Returning to this country in 1887 he joined the firm of Messrs. Siemens Brothers and became personal assistant to Alexander Siemens, ultimately taking charge of the drawing office, where he found ample scope for his industry and originality. He assisted in the design of the electrical equipment of the first locomotives built for the City and South London Railway, and this experience, no doubt, engendered the great interest in electric traction which he never relinquished. During this period he attended classes at the Finsbury Technical College, where he came under the influence of John Perry and Silvanus Thompson, and much of his later success as a teacher may be attributed to the inspiration received from them. Interesting himself in the design of the electrical machinery for the new laboratories at King's College, endowed by Lady Siemens, he came in contact with Dr. John Hopkinson who, in 1890, accepted the newly founded Siemens chair of electrical engineering, and who appointed him demonstrator in 1891. By reason of the extensive consulting practice which occupied much of Hopkinson's time a large share of the responsibility for the organization and administration of the

new department devolved upon Wilson, and in recognition of this he was appointed assistant professor in 1898. In the following year the tragic death of Hopkinson occurred and Wilson was appointed to the chair, which he filled with great distinction until his retirement in 1930, after 40 years of devoted service. His success as a teacher may be attributed to the possession of an infinite capacity for taking pains, together with an almost unequalled devotion to his students, who responded to his efforts on their behalf. In addition to being an indefatigable worker at college, he was no less active as a writer, for he published about 80 of his own and some 30 conjoint papers. His well-known textbook entitled "Electrical Traction" was published in 1897, and a second edition, written in collaboration with Mr. F. Lydall, appeared in 1907. Although not among the very few fortunate enough to originate a development of outstanding importance, Wilson found ample scope for his inventive mind, and it was not long before he had several patents to his credit. Among others may be mentioned the laminated-field single-phase and polyphase alternating-current commutator motor which he invented in 1888. He was also a pioneer worker in wireless telegraphy, for he carried out, at the request of Sir William Preece, the first tests made in this country on Marconi's apparatus. These trials were conducted in 1896 on the terrace at King's College. He soon after invented a magnetic detector of novel construction and took out several patents for apparatus of this type. He also carried out extensive experiments on feebly magnetic substances, and in 1921 delivered, before the Institution, three lectures on "Magnetic Susceptibility of Low Order," for which he was awarded the Kelvin Premium. Over 30 years ago he commenced to investigate the effect of atmospheric exposure upon the conductivity and tensile properties of various light alloys used as conductors, and from time to time made valuable reports regarding their endurance. He took an active part in the organization of the University of London, and served as secretary to the Board of Studies in Electrical Engineering from its foundation in 1901 until 1907, when he became chairman of the Board. He held this office until 1912, when he was appointed dean of the Faculty of Engineering in the university, a post which he held until 1916. On his retirement in 1930 his services to the university and his long and distinguished scientific career were recognized by the conferment upon him of the title of *Professor Emeritus*. He was elected a fellow of King's College in 1909. During the last two years of his life he held the position of special lecturer and, as a consequence, was able to devote himself to advising and helping students, both past and present, in their efforts to secure employment, and it was gratifying to him to see that this was attended with a considerable measure of success. Possessing a retiring and modest nature, he made little effort to bring himself or his work to the notice of the public or even of the engineering profession, but, on the other hand, few teachers could claim so large a circle of friends or so sincere a regard as that in which he was held. He was elected a Member of the Institution in 1890, and served on the Council from 1929 until his death, which took place on the 17th February, 1932. J. K. C.-S.

STEPHEN NEWCOME WILSON was born on the 26th December, 1864, and was appointed to the Indo-European Telegraph Department of the Government of India in February 1883. Ten years later he was specially selected to make a survey for a telegraph line from Las Bela to Kuhak, and afterwards was almost continuously employed in the survey, construction, and maintenance of the telegraph lines in Makran. His most important work was the construction of the line from Karachi to Nok Kondi, a length of 520 miles through remote and difficult country where the inhabitants were frequently unfriendly and sometimes hostile. He showed conspicuous ability in his dealings with the rather difficult peoples inhabiting that part of the world. They got to know him well and trusted him, so that his influence proved a real help to the political authorities in the troublesome times of the War when foreign agents were busy trying to stir up disaffection. Towards the end of his service he was appointed assistant director, and he retired in 1920 after 37 years' valuable service. He was elected an Associate of the Institution in 1887, an Associate Member in 1899, and a Member in 1907. M. G. S.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the title or subject of a paper or address.
(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.
(D) indicates a reference to a discussion upon a paper of which the title is quoted.
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